A STUDY ON OPTIMIZING INFRARED HEATING TECHNOLOGY FOR ASPHALT PAVEMENT MAINTENANCE AND REHABILITATION

by

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AUTHOR’S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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ABSTRACT

In Canada especially, cracking and potholes on asphalt concrete pavements is a continuous problem requiring constant repairs. With the increased expansion and use of asphalt pavement infrastructure, combined with more severe climactic conditions and freeze thaw cycles experienced by asphalt pavements, pavement maintenance and repair practices need to improve the quality and longevity of their repairs.

When compared to current standard crack and pothole repair processes such as crack sealing, crack filling, and full milling and replacement, infrared heating repairs can consistently provide a longer lasting repair then crack sealing, crack filling, and mill and replace patch repairs. Infrared heating repairs provide a repair which is more cost effective than full roadway replacement, with significantly longer lifespans than most conventional repair methods, filling in an intermediary repair gap present in the current pavement maintenance roster.

The City of Waterloo cooperated with University of Waterloo's Centre for Pavement and Transportation Technology and infrared heating manufacturer Heat Design Equipment Inc. (HDE) to evaluate the use of infrared heating repairs on a local project. This project was located along Sugarbush Drive which requires major pavement rehabilitation. Upon visual inspection, and laboratory testing completed on the asphalt, granular base course, and subgrade materials, results indicated that Sugarbush Drive was a prime candidate for infrared heating repairs, mainly because the sampled asphalt cores contained high percentages of asphalt binder. It was recommended that the City of Waterloo proceed with the use of infrared heating technology to repair the entirety of Sugarbush Drive, and continue partnership with CPATT to observe and record the performance of the repair throughout the road's lifespan.

The development of a patching mixture utilizing infrared heating consisted of using reclaimed asphalt pavement (RAP) and rejuvenating agents. The properties of three different RAP sources were evaluated through laboratory testing in order to determine their respective performance gradings. Good performance was achieved from two of the standard RAP sources retrieved from previously used milled asphalt pavement materials from the region, however, extremely high

stiffness was observed from a RAP source consisting of unused excess asphalt mixtures, and further testing was recommended to confirm the properties of the RAP source.

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CHAPTER 1

INTRODUCTION

Asphalt concrete pavement design has evolved significantly since it started being used in the late 1800s (National Asphalt Pavement Association 2019). Through the use of different materials, designs, maintenance and rehabilitation treatments, the durability, flexibility, and service life of asphalt pavement roadways has significantly increased. Despite these advancements, cracking and potholes are still a common occurrence in asphalt concrete roadways. This kind of pavement damage can be caused by fatigue, as well as the constant expansion and contraction of the pavement during freeze-thaw cycles.

Climate change continues to cause more adverse weather conditions worldwide including increased temperature extremes, precipitation, solar radiation, and extreme weather events (Y. Qiao, A. Dawson, T. Parry 2016). These environmental changes severely affect the performance of pavement structures, reducing service lives significantly. One study completed in 2007 estimated a 30% increase in rehabilitation costs for flexible pavement structures solely due to the adverse effects of climate change (Cechet 2007).

In most regions of Canada, cold winters as well as hot summers are experienced. This great temperature variation significantly changes the characteristics of asphalt binder by increasing viscosity and decreasing penetration and ductility, and thus vastly accelerates the degradation of asphalt pavements, creating more premature cracks and potholes throughout the country. There is a vast network of paved highways and roadways across Canada, totaling approximately 415,000 km (Kang and Adams 2013). Due to the extent of roadway infrastructure, some sections of pavement within the roadway system are always in need of maintenance or repair work. At the network-level, owner agencies involved in pavement management must assess a large number of assets to identify the most cost-effective and sustainable maintenance and rehabilitation methods (commonly referred to as "M&R”). At the project-level, the agencies must evaluate and select the best maintenance or repair alternative from the feasible techniques.

In Ontario, the Ministry of Transportation maintains approximately 40,000 km of asphalt pavement highway lanes. From 2016 to 2025, $14 billion will be spent on maintaining and rehabilitating these roadways (Lysyk 2016). Increased formation of cracks and potholes in Ontario roadways is making it very difficult for the Ministry to keep up with the constantly growing number of crack repair projects.

There are many existing methods of performing crack and pothole repairs on asphalt pavements. Often one method is preferred because it is the traditional "tried and true" technique which has the benefits of having well understood performance and a construction process familiar to contractors. However, with advances in materials and technology there are new pavement repair methods being developed that promise advantages over the traditional methods with regards to cost, sustainability, performance, and constructability. The drawbacks associated with a new technology are an uncertain long-term history of performance and inexperience in the design, construction, and maintenance process.

To properly address cracks and potholes, municipalities and road authorities typically implement the current standard crack repair techniques which include crack sealing, crack filling, and mill and replace. All these methods, especially completely milling and replacing a section of roadway, utilize virgin asphalt materials to repair the affected areas. In Canada, approximately 4 million cubic metres of asphalt is sold annually, 80% of which is used for paving applications (Statistics Canada 2017). The creation of asphalt significantly contributes to the nation's carbon footprint, with the life cycle carbon footprint of an average asphalt plant being 80,962 t CO_2-e (Karjalainen 2019). This is assuming an annual asphalt mix production of 150,000 tonnes over a 15 year lifespan. When this asphalt has reached its service life on a roadway and is removed, a small portion of the removed asphalt material, known as Reclaimed Asphalt Pavement (RAP) often gets added into Hot Mix Asphalt (HMA), while the rest is typically stockpiled. These stockpiles represent inefficiencies in the asphalt industry. Many of the chemicals and materials making up this RAP are still effective and usable (Willis and Marasteanu 2013).

A pavement repair method is needed that can manage the continual deterioration of asphalt pavement structures. Ideally, a solution that will utilize the growing stockpiles of RAP materials. Infrared heating repairs have this potential. This paper will explore the method of infrared heating for asphalt pavement repairs, including analyzing system processes, quantifying the effects of using RAP materials with this method, and evaluating the performance of these repairs.

1.1 Research Background

Heat Design Equipment Inc. is a manufacturer of infrared heating machinery for use in the construction and maintenance/repair processes of asphalt pavement surfaces. They have partnered with the University of Waterloo's Centre for Pavement and Transportation Technology (CPATT) in order to further research the effects of infrared heating repair methods and validate their ongoing success with them.

Two major projects have been the focus of this partnership: First is a project aiming to create an asphalt patching mixture with infrared heating containing 100% RAP materials. The second project is in collaboration with the City of Waterloo and involves the rehabilitation of a residential street using infrared heating technology.

1.1.1 Infrared Heating

Infrared heating is a relatively new heating technology in pavement preservation treatments for fixing cracks and potholes. This technology utilizes infrared light to evenly heat the pavement surface. Infrared light is not visible to the naked eye because it consists of much longer wavelengths then all visible light. When objects are exposed to infrared radiation they absorb these rays in the form of heat (Ray-Tech Infrared Corp. 2017). The purpose of this machinery is to heat the existing asphalt in a damaged area until it is malleable enough at a specified depth to rework.

The infrared machinery works by using propane fed into a heater plenum through a device that mixes the proper amount of air with propane to cause ignition. Each infrared heating segment uses 100,000 Btus, which is equivalent to the amount of propane used by two typical household barbeques. Ignition occurs within a ceramic cloth so that the cloth heats up to a temperature range of 800 to 1000°C at the outside face of the ceramic. This hot surface emits infrared radiation until it impinges on a body (the asphalt in this case) at which point it turns into heat as it travels through the solid. In less than ten minutes the blanket can heat the asphalt to 350°C, 2.5 inches deep (Kieswetter 2013). The area heated to these specifications will typically be 2 inches from the outside perimeter of the infrared heating machinery. The temperature of the ceramic cloth can be adjusted by decreasing the gas pressure so there is control over the amount of infrared that impinges the surface of the asphalt. Figure 1.1 below displays an infrared heating machine with a close up on the heated ceramic cloth.

Figure 1.1: Left: Infrared Heating Machine in Use, Right: Bottom of Machine in Use (Kieswetter 2013)

The infrared heating machines are typically composed of multiple individually controlled infrared heating segments. On the right side of Figure 1.1 above the ten rectangular segments are easily identifiable. In order to contain the infrared heat and focus it on the desired pavement surface, flaps are often installed on the sides of the infrared machine. These flaps also assist in keeping the temperature consistent inside of the heated area, and block the wind from cooling down the process, making the machines more efficient.

Infrared heating repairs are most commonly performed during construction season, but can be performed in the winter if necessary. Due to the cold air and cooler initial pavement temperature in the winter, the area will take longer to heat up, and the effectively heated surface area of the patch will reduce approximately 4-6 inches along the perimeter of the infrared heating machine (Heat Design Equipment Inc. 2019).

The process of repairing a section of pavement with infrared heating is as follows: Firstly, the affected pavement area, as well as a perimeter of surrounding pavement, is heated, making sure the pavement is evenly heated to 350°C past the depth of any cracked areas or deficiencies. Workers then rake and mix the now malleable asphalt in place to remove damages, starting from the outer edges of the heated area and working their way in (Uzarowski et al. 2011). In some cases, typically during pothole repairs when a significant amount of asphalt has been removed from the site, additional asphalt will be added at this point to make the affected area level with the surrounding pavement. During the scarifying process, workers add rejuvenators to the hot asphalt in order for the affected pavement to regain some of its innate properties that it loses over time. When asphalt pavement ages it becomes more stiff, hard, and prone to cracking; adding the rejuvenators when the pavement is soft makes the pavement more flexible. The entire heated area is then compacted, creating a strong thermal bond between the reworked pavement area and the surrounding pavement which was also heated (Parker 2007). Once the pavement surface has cooled down to approximately 50°C, regular traffic flow can continue. Figure 1.2 below shows the general process for repairing a section of pavement with infrared heating.

Figure 1.2: 1) Infrared Heating 2) Scarifying 3) Rejuvenators Added 4) Compaction (Kieswetter 2013)

It has been found that there is a time limit to heat the surface until it gets overheated. Overheating may evaporate the rejuvenators and even burn the asphalt binder, so not overheating the pavement surface is the main challenge of reheating the asphalt in place (Park 2007). Compared to more conventional heating methods such as hot air and open flame, infrared heating technology can heat a pavement surface longer and to a higher temperature at a specified depth before causing any damage to the materials (Parker 2007).

1.1.2 Sugarbush Drive Rehabilitation Project

When establishing a new pavement repair method such as infrared heating, it is extremely important to create connections to significant clients with notoriety and many project opportunities. Heat Design Equipment Inc. (HDE) is a Kitchener/Waterloo based company specializing in the creation and manufacturing of infrared heating machinery solely for asphalt pavement repairs. The City of Waterloo has been hesitant to utilize infrared heating in their pavement repairs in the past, but through a research partnership with CPATT, the City of Waterloo was willing to try using infrared heating repairs during rehabilitation of a small, residential roadway called Sugarbush Drive.

1.1.3 100% RAP Patching Mixture

When repairing deteriorated roadways with significant asphalt loss, virgin materials are almost always used to bring the surface up to grade. This is the perfect opportunity to use an asphalt patching mixture made with RAP materials instead.

To create an asphalt patching mixture on site, a portable asphalt heater is used. These machines are used to reheat loose asphalt mixtures, including virgin HMA or RAP, into a malleable state before application. A reliable heating operation ensures that RAP remains loose with no agglomeration and the rejuvenators can be dissolved uniformly and effectively within the aged asphalt binder (Nazzal et al. 2015). Asphalt heaters have been developed using conventional hot air or open flame heating methods, as well as infrared heating technology. For this project, only the infrared heating method will be considered due to its superior heating abilities and track record of burning fewer materials. Figure 1.3 below displays an infrared heating portable asphalt recycler.

Figure 1.3: Portable Asphalt Recycler (Heat Design Equipment Inc., 2017)

Asphalt mixtures created by using these infrared heating machineries have not been formally tested and an optimal mix design for 100% RAP with the right type and dosage of rejuvenators is in need. The goal of this project is to develop an asphalt mix which can be effectively used as a patching / filling mixture during infrared heating repairs, containing as much RAP material as possible.

1.1.4 Research Benefits

Great economic and environmental benefits can be achieved if the quantity of RAP can be increased in pavement design, construction, maintenance and rehabilitation. In the more remote regions of Canada especially, where small townships and native reservations are widely dispersed, access to the pavement materials and equipment is scarce, and the expense of shipping virgin materials to these regions is enormous. With the right combination of rejuvenators and infrared heating technology using 100% RAP materials to maintain pavement surfaces, these regions can greatly reduce the expense, energy used and emissions created for these pavement repairs. In summary, this research will contribute to the scientific knowledge in Canada by:

- Evaluating and comparing the properties of different sources of RAP created by infrared heating and traditional gas burners.
- Evaluating and quantifying the effects different types and dosages of rejuvenators have on RAP performance.

- Evaluating the lab and in-service performances of mixtures using 100% RAP.
- Developing an optimal mix design using 100% RAP with and without virgin materials for the applicable implementations.
- Evaluating and verifying the economic and environmental benefits of RAP in pavement construction and preservation.
- Improving the sustainability of Canadian roads by improving the design, construction and maintenance techniques using RAP.

1.2 Scope

This report explores the validity of using infrared heating as a pavement repair strategy. This includes comparing the quality of the infrared heating repair method to standard practices, a case study exploring the decision making process involved in choosing an infrared heating style of repair, and using infrared heating to create a pavement patching mixture composed entirely of RAP materials.

When comparing the performance of infrared heating repairs to more commonly used methods, only the following repair strategies are considered:

1. Crack sealing
2. Crack / pothole filling with virgin materials
3. Conventional milling and repaving

No laboratory or field testing machinery was used for this first study, however, several case studies are considered during this comparison. Long term field performance studies on infrared heating repairs are lacking, but several field inspections of previous infrared heating repair sites are included in the evaluation.

The scope for the Sugarbush Drive project includes a preliminary assessment of the roadway, borehole sampling, lightweight deflectometer (LWD) testing, and laboratory testing to evaluate the current condition of Sugarbush Drive. The laboratory testing completed on the collected materials include binder extractions, gradation analysis and proctor testing. Multiple maintenance/rehabilitation options involving the use of infrared heating are created and proposed to the City of Waterloo for evaluation. Beyond this, a preliminary design of the recommended maintenance strategy was completed.

This report covers the research plan, methodology, and current progress of the 100% RAP patching mixture project. This includes the collection, laboratory testing, and analysis of the three base RAP materials considered for this project. Laboratory testing completed on the RAP material is as follows:

- Binder extraction
- Gradation
- Rolling Thin-Film Oven (RFTO)
- Bending Beam Rheometer (BBR)
- Dynamic Shear Rheometer (DSR)

1.3 Objectives

The primary objective of this research is to understand the effects of infrared heating on pavement maintenance and repair projects, with particular emphasis on the use of infrared heaters during crack and pothole patch repairs. The following specific objectives of this thesis include:

- Evaluating the advantages and disadvantages of infrared heating, focusing on previous studies validating the performance of the repair method.
- Comparing the effects of infrared heating asphalt pavement repairs to other conventional pavement repair methods.
- Developing a matrix which utilizes the main decision factors when choosing a pavement repair method, highlighting the advantages and disadvantages of each repair option.
- Designing a suitable maintenance strategy for Sugarbush Drive, located in the City of Waterloo.
- Designing a 100% RAP patching mixture using new infrared heaters.
- Characterising the three different RAP sources to be used in the 100% RAP patching mix designs.

1.4 Organization of Thesis

Chapter 2 consists of a literature review covering information pertinent to previous research completed on infrared heating as it pertains to the two major projects covered in this thesis. Chapter 3 compares the quality of infrared heating crack and pothole repairs to those achieved by more commonly used maintenance repair strategies. Chapter 4 summarizes the progress of a project involving the repair of Sugarbush Drive using infrared heating technology. Chapter 5 discusses the progress made on the creation of a pavement patching mixture using 100% RAP materials and infrared heating. Chapter 6 provides conclusions and recommendations for future work.

CHAPTER 2

LITERATURE REVIEW

This chapter provides a summary of previous studies pertinent to the infrared heating research covered in this thesis.

2.1 Use of Infrared Heating

This section summarizes the current uses of infrared heating in Canada and around the world. Previous research regarding the quality of infrared heating repair applications, including multiple case studies, is examined as well.

2.1.1 Infrared Heating Applications

Infrared heating repairs are very versatile as they can repair a wide variety of pavement deficiencies of different sizes and levels of severity. The extent of research on these different applications of infrared heating technology is summarized in the following section.

2.1.1.1 Patch Repairs

By far the most common use of infrared heating technology repairing asphalt pavement is patching, where the affected area is cleaned, heated, scarified while adding rejuvenators then supplemental asphalt, before finally being compacted. This basic patching process was described in detail in Chapter 1.

The key component contributing to the success of this style of patch repair is the thermal bond created between the repaired asphalt and the surrounding in place material. A thermal bond requires both bonding materials to be heated during compaction. Compared to a cold joint, a thermal bond provides increased density at the joint, allowing less water and material to penetrate (Kandhal and Rao 1994; Daniel 2006).

2.1.1.2 Longitudinal Crack Repairs

Longitudinal cracking is an extremely common roadway deficiency which forms parallel to the centreline of the roadway, and is most typically caused by the reflection of a joint in the pavement, or poor joint construction (Decker 2016).

Specialized infrared heating machines have been designed for longitudinal crack repairs. It is composed of multiple infrared heating devices linked together from end to end forming a 48 foot long “train”. This chain of infrared heating devices can be towed by a bobcat or any other small construction vehicle. During maintenance repair of longitudinal cracking, this machine can be continuously towed along the affected area at a rate of 5 feet/minute (Heat Design Equipment Inc., 2017). By the time the affected pavement has been heated by the entire length of the train, it is at the correct temperature to be scarified, reworked, rejuvenated and compacted by the maintenance workers. Figure 2.1 below displays this machine in use.

Figure 2.1: Infrared Heating Train (Heat Design Equipment Inc., 2017)

2.1.1.3 Joint Heating

When constructing a longitudinal joint one would ideally pave the entire width of roadway at once, or have pavers pave in echelon so the longitudinal joint has a thermal bond connecting it. This is not always feasible or cost effective for every project, so most often roadways are paved one lane at a time, with a cold joint connecting them. Many different strategies have been developed to optimally connect to this cold joint including creating a wedge or tapered edge on the joint, cutting back the cold joint before paving the next lane, overlapping the cold joint with hot mix, and various methods of compacting the longitudinal joint (Vefa Akpınar 2004). Although each of these longitudinal joint construction methods work with varied levels of success, severe longitudinal joint cracking is still extremely common when constructing asphalt pavement roadways with a cold joint. Kandhal and Rao state that longitudinal joint cracking results primarily from the lower density gradient which is usually encountered across a cold joint (Kandhal and Rao 1994). The unconfined edge from the first paved and cooled lane has a low density while the hot paved lane connected to it has a high density. The resultant density at the cold join is typically 1%-2% lower than the rest of the roadway, allowing water to penetrate the joint and cause premature cracking, usually within a year after construction (Kandhal and Rao 1994; Daniel 2006). Multiple studies on longitudinal joint construction have concluded that no matter what extra measures are taken during cold joint construction, the performance is still inferior to what a hot joint provides (Kandhal and Rao 1994; Vefa Akpınar 2004; Daniel 2006).

Another use for infrared heating machinery is to remove this problematic cold joint by heating up longitudinal joints during construction to ensure a thermal bond with the asphalt alongside. To achieve this hot joint, an infrared heating train would heat up the new cold joint between lanes with the asphalt paver following. Figure 2.2 on the next page displays this longitudinal joint construction technique as used in Hamilton, Ontario.

Figure 2.2: Placement of Surface Course Using Infrared Joint Heater on Rymal Road, Hamilton in 2008 (Uzarowski et al. 2009)

Compaction tests of Rymal Road after construction indicated 95% compaction, and the average compaction of the longitudinal joint was 94.2% (Uzarowski et al. 2009). A study completed at the University of New Hampshire compared the performance of infrared heated construction joints to conventional cold joint construction and concluded a significant performance improvement when using infrared heaters (Daniel 2006). Utilizing the longitudinal infrared heating train for joint construction is an effective preventative maintenance strategy, which will decrease the maintenance requirements for the roadway (Heat Design Equipment Inc. 2019).

2.1.1.4 Full Roadway Rehabilitation

A larger infrared heating machine can be developed to operate this train style seamless repair over an entire lane or roadway width (Heat Design Equipment Inc. 2019). Current large infrared heating machines could be used in this manner, but they would have to move very slowly in order to properly heat the pavement surface. A more ideal configuration would consist of additional heaters on the end of the wide patching devices to make them longer, but not so many that they become too difficult to transport.

2.1.2 Case Studies

This section of the literature review covers 4 different case studies involving the use of infrared heating repairs, and the quality or repair provided. These studies provide a practical perspective on the effectiveness and lifespan of various infrared heating repair applications.

2.1.2.1 Case Study No. 1 – Bleams Road Waterloo, Ontario

An example of infrared heating technology chosen as the pavement repair method for a project is in the Region of Waterloo on Bleams Road. This project began in 2008 with the resurfacing of Bleams Road. The binder course was placed in 2008 and the Region of Waterloo decided to wait two years before placing the surface course. In 2010 however, several low to medium severity cracks had propagated on the binder course and required attention before placing the surface course (Uzarowski et al. 2011).

The Region of Waterloo required a cost effective, long term repair solution for these cracks. As this road was newly resurfaced and expected to last a long time, it was very important to use the most effective method possible to repair these cracks. The Region of Waterloo chose to use infrared heating to repair the cracked areas on Bleams Road because it provided a long term repair solution, used the in-place materials which were only two years old, and is very cost effective because there were local experts in the infrared heating industry stationed in Waterloo (Uzarowski et al. 2011). Figure 2.3 on the following page displays cracking on Beams Road before and after the infrared heating repairs.

Figure 2.3: Left – Cracking on Bleams Road; Right – Repaired Cracking on Bleams Road (Uzarowski et al. 2011)

This surface continued to perform well beyond a year after it was repaired with no surface distresses visible, and no signs of cracking from the binder course (Uzarowski et al. 2011). Density measurements were performed and cores taken across some of the repaired cracks to further evaluate the quality of repair. Density measurements recorded were within the required range of 92%-96.5%, and the cores taken displayed a strong bond still in place between the new and existing pavement (Uzarowski et al. 2011).

2.1.2.2 Case Study No. 2 – Kuujjaq Airport, Kuujjaq, Quebec

In Kuujjaq, Quebec, a large transverse crack in the middle of the runway was causing continual problems for aircraft taking off and landing. The crack had sealant applied in it many times but the repairs were not lasting long. In 2013, Kuujjaq Airport decided to implement infrared heating repairs as a long term repair solution for the large crack. When repairing a crack with infrared heating in which crack sealant has been applied in the past, the crack sealant must be removed before scarification. After the area has been heated, it is quick and easy to remove old crack sealant before adding rejuvenators to the heated asphalt and scarifying (Kieswetter 2013). Kuujjuaq Airport has experienced success with the infrared heating patch, and has not considered additional repairs for this runway in the 6 years since. Figure 2.4 shows the crack in question before and during the infrared repair process.

Figure 2.4: Kuujjuaq Airport. Left: Crack Before Repairs; Right: Crack During Infrared Heating Repairs (Kieswetter 2013)

Other runway/taxiway repair projects which have utilized infrared heating as their maintenance method include Jean Lesage International Airport in Quebec City used infrared heating while resurfacing a runway, Fort Drum Air Base in New York utilized infrared heating for longitudinal joint construction, and Vancouver International Airport recently used infrared heating for some patch repairs (Kieswetter 2013).

2.1.2.2.1 Infrared Heating Repairs on Airfield Surfaces

Runways and taxiways, unlike airport apron areas, are designed to withstand short term loading by aircrafts taking off, landing, and taxiing. The most common asphalt pavement distress types for airport runways and taxiways are longitudinal cracking, transverse cracking, weathering, block cracking, rutting, ravelling, jet blast and oil spillage (Hajek, J., Hall, J.W., Hein 2011). Routine maintenance is essential in order to stop these distresses from occurring and propagating, causing unsafe conditions for airplanes.

When operating larger aircraft, pilots cannot properly see the pavement surface around the wheels of their aircraft, so it is vital there are no major pavement distresses to cause damage to the aircraft or veer them off course. When travelling at high speeds during takeoff and landing, running into any sort of debris could severely damage the aircraft. Common airfield pavement distresses, including cracking and potholes, can loosen small chunks of pavement, increasing foreign object damage (FOD) risk for aircraft (Bennett 2007). Compared to other small area crack sealing and patching, infrared heating repairs bond all surfaces within the applied area together, providing the repair with less opportunity for chunks of pavement to come loose, decreasing FOD risks.

2.1.2.3 Case Study No. 3 – Waterloo Street, New Hamburg, Ontario

In 1997, a large transverse crack crossing the entirety of Waterloo Street in New Hamburg Ontario was repaired using an infrared heating patch. Density measurements were taken on the patched area immediately following the repair, averaging 97% (Uzarowski et al. 2011). Asphalt cores were taken from the repaired area and some adjacent pavement sections on Waterloo Street exhibiting no signs of distress. After some laboratory tests were completed, it was concluded that the repaired asphalt exhibited slightly lower flow, stability, and Voids in the Mineral Aggregate (VMA) then the adjacent unrepaired area (Uzarowski et al. 2011). Gradation analysis on the sampled asphalt cores indicated the repaired area had a noticeably finer gradation. The differences in test results were considered to mainly be due to the introduction of virgin asphalt mix to the fixed area during repairs (Uzarowski et al. 2011).

Throughout the service life of the repair, the area performed well structurally and only one additional repair was required in that area due to reflective cracking. The entirety of Waterloo Street was repaved in 2010, giving the infrared patch a successful service life of 13 years (Uzarowski et al. 2011).

2.1.2.4 Case Study No. 4 – Longitudinal Joint Construction in Tennessee

The state of Tennesee had experienced continuous longitudinal cracking problems along construction joints, so a study was completed by the University of Tennessee to investigate the fundamental mechanisms of longitudinal joint failure in Tennessee, evaluate several available technologies and construction practices that could mitigate HMA longitudinal joint failures, and recommend necessary changes to the Tennessee Department of Transportation (TDOT) specifications to ensure higher quality longitudinal joint repairs in the future (Huang and Shu 2010). It was determined that the main cause of these longitudinal joint failures was ineffective joint construction techniques, mainly due to the fact that Tennessee only utilized cold joint construction. The effectiveness of different longitudinal joint construction techniques was field tested using a nuclear gauge density test and a permeability/vacuum test, and asphalt cores were sampled to complete laboratory tests on including direct air void content, permeability, indirect tensile (IDT) strength, water absorption, and X-ray CT tests. The longitudinal joint construction techniques analysed were conventional cold joint construction as a control, rolling from hot side 6 inches away from joint, notched wedge joint, cutting wheel, infrared heating, joint maker, and restrained edge. Several joint sealers and joint adhesives were also analyzed.

The study concluded that the infrared heater exhibited the best performance among all of the joint construction techniques evaluated in the study. Infrared heating the cold joint before paving was proven to reduce the air void content and water permeability, while increasing IDT strength. The air voids distribution obtained from the X-ray CT images showed that the effectiveness of infrared heating in improving joint quality was through increasing the compaction degree of longitudinal joint deep to the overlay bottom, thus making the joint denser (Huang and Shu 2010).

This study references another similar case study completed by the Kentucky Transportation Center, which compares the effectiveness of notched wedge joint, restrained wedge, joint maker, infrared joint reheater, and joint adhesives as longitudinal joint construction techniques and also concluded that infrared heating provided the highest joint density (Fleckenstein, Allen, and Schultz Jr 2003).

2.1.3 Summary of Case Studies

Four different case studies regarding the use of infrared heating repairs were reviewed and are summarized in Table 2.1 below.

Table 2.1: Summary of Case Studies

Case Study	No. 1	No. 2	No. 3	No. 4
Location	Bleams Road Waterloo, Ontario	Kuujjuaq Airport, Kuujjuaq, Quebec	Waterloo Street, New Hamburg, Ontario	Various, Tennessee, USA
Surface	2 Lane Roadway Binder Course	Runway Surface Course	2 Lane Roadway Surface Course	Highway Surface Courses
Deficiency	Cracking	Transverse Crack	Transverse Crack	Longitudinal Joint Construction
Lifespan	13+ years	6+ years	13 years	N/A
Density	92%-96.5%	N/A	97%	Highest of Tested (Above 92%)
VMA	N/A	N/A	Lower than Unrepaired Area	Lower Deeper than all other Tested Methods

When tested, all infrared heating procedures produced low VMA and high density asphalt pavement surfaces, resulting in long lifespans. All four case studies displayed practical examples of infrared heating repairs performing successfully.

2.2 Reclaimed Asphalt Pavement

Reclaimed asphalt pavement (RAP) is the reprocessed materials collected from milling existing asphalt surfaces during maintenance/rehabilitation, or resurfacing procedures (Copeland 2011). RAP contains course aggregates and asphalt binder material that can be reused to create new hot mix asphalt (HMA). RAP is also commonly used in granular base or subbase materials to stabilize the base aggregate or an embankment (Copeland 2011). After the material is milled and removed from site, it’s processed by blending and crushing until a consistent gradation is achieved. In general, mixtures containing high amounts of RAP have increased stiffness, which improves rutting resistance, but reduces low temperature and fatigue performance which associates with increased thermal and fatigue (bottom-up) cracking (Forfylow 2011).

In Ontario, the use of RAP material is governed by the Ontario Provincial Standards and Specifications (OPSS) 1150. This standard allows a maximum of 15% RAP by mass inside surface course mixtures (HL 3, HL 3F, HL 4, and HL 4F), and 30% in binder courses (HL 4, HL 8) (OPSS 2018). HL 4 and HL 8 mixtures with up to 50% RAP materials may be allowed, but require additional testing to prove the mixture meets specifications, and written approval by a contract administrator (OPSS 2018). This option is not common among projects in Ontario because of the extra effort required and because mixtures with greater than 20% RAP must differ in gradation than conventional mixtures, with no current standard outlining best practice mix designs and performance standards for them (Ambaiowei 2014). Throughout the rest of Canada, higher percent RAP mixtures are slightly more common, with the provinces of Manitoba, Saskatchewan, and British Columba placing no limit on the percentage of RAP allowed in HMA mixtures. Other countries including the United States, Australia, South Africa, Japan, Germany, France, United Kingdom, and other European countries have also used RAP materials in HMA with great success (Stephanos and Pagan-Ortiz 2011; Merrill, Nunn, and Carswell 2004).

2.3 Rejuvenators

Due to the densification effect of asphalt mixes under repeated traffic loads, a high RAP content will result in increased stiffness of the asphalt mixtures and susceptibility to fatigue cracking and low temperature cracking (Sabouri et al. 2015; Tran et al. 2017; Shu, Huang, and Vukosavljevic 2008). For these reasons, the commonly used approach to improve the quality of high content RAP mixture is to add rejuvenators or recycling agents. Rejuvenators, which generally consist of low-viscosity oil and certain modifiers, can be roughly divided into three types: asphalt-based, coal-tar-based and bio-based (Walck et al. 2018). Overall, coal-tar-based rejuvenators have dominated the market while bio-based rejuvenators made of agricultural products are still being tested. Existing researchers have found that the dose and type of rejuvenator have effects on mixture and binder properties (Mogawer et al. 2013). Specifically, asphalt rejuvenators improve cracking resistance by mitigating the stiffness of the aged binder, and the dosage and test conditions can adversely impact the rutting and moisture susceptibility. The relationships between RAP performance and rejuvenator content seem linear, which can help determine the dosage of rejuvenator when Superpave performance grade (PG) requirements at the three temperatures are satisfied (Zaumanis, Mallick, and Frank 2014; Shen and Ohne 2002). However, the complicated mechanism of interaction between the rejuvenator and RAP is still unclear, so the type and dosage of rejuvenators and their effectiveness will be another area of study in this research.

2.3.1 Alternative Rejuvenator Substances and Additives

Beyond standard rejuvenating agents, other materials have flexibility and durability properties that could benefit an asphalt patching mixture. Using more recycled materials such as crumb rubber, roofing shingles, or waste plastics can further decrease the carbon footprint of asphalt mixes. Other material additives such as fibre reinforcement could possibly improve properties of the mix as well.

Huge stockpiles of scrap tires exist across Canada, which not only are a waste of space and usable resources, but are a constant danger of creating tire fires which release harmful toxins into the air and are very difficult to extinguish (Mashaan et al. 2014). Crum rubber is created from scrap tires being shredded and grinded into a uniform mixture with particle sizes ranging from 4.75mm to 0.075mm (Way, Kaloush, and Biligiri 2012). This material is used in playgrounds as a sand substitute, in landscaping applications, as well as in asphalt roadway mixtures (Ambaiowei and Tighe 2013). A study by Doubra Charles Ambaiowei at the University of Waterloo concluded that "Combining RAP with CRM (Crumb rubber modified asphalt) is capable of compensating for RAP shortfalls such as its effects on binder aging and mix stiffness, thus improving the mixture's stability, durability, impermeability, workability and flexibility" (Ambaiowei 2014). Incorporating crumb rubber into a 100% RAP patching mixture can therefore result in performance and environmental benefits.

Asphalt roofing shingles typically last only 15-20 years, producing a large quantity of waste. One and a half million tons of asphalt roofing shingle waste is generated each year in Canada, 90% of which is dumped into landfills (Islam 2011). They are composed of asphalt cement (AC), fine aggregates, filler, and fibres, 30% by mass of which is AC (Islam 2011). It appears to be an ideal pairing mixing recycled asphalt shingles (RSA) with RAP in an asphalt patching mixture, the AC in the RSA should complement the lack thereof in the RAP. A study completed by University of Waterloo's CPATT tested incorporating RSA into Ontario standard HMA mixtures containing RAP. It concluded that "Lowering the temperature performance grade of asphalt binder by 6 °C and incorporating 3% RAS or less with RAP in HMA mix design can meet the appropriate specification" (Yang et al. 2014). However, the asphalt binder in RSA was typically tested to be stiff, similar to that present in RAP materials making the mixtures performance less than ideal at low temperatures (Yang et al. 2014).

It is well known that asphalt pavement performs much better in compression then tension. In theory, the addition of fibres with high tensile strength to the asphalt mixture will allow the tensile stresses the pavement experiences to be transferred to the fibres. Many different fibre materials have been tested in asphalt cement including cellulose, synthetic polymers, glass, tire fibres, asbestos, lignin and coconut fibres (Chowdhury, Button, and Bhasin 2006; Kaloush 2014). Fibre reinforcement has been proven to improve crack resistance, rutting resistance, and freeze thaw resistance to HMA mixtures (Chen et al. 2009; Biligiri, Rodezno, and Nadkarni 2008; Aramid 2019). Fibre reinforcement has been used in asphalt mixtures containing low percentages of RAP material, but not often with high amounts of RAP (Aramid 2019).

The growing amount waste produced by plastic products such as bottles, containers, and electronics has developed into a serious disposal problem for all of this material (Mashaan, Rezagholilou, and Nikarz 2019). Incorporating the tensile strength and flexibility of plastics into asphalt mixtures could be extremely useful, especially to high percent RAP mixtures. In order to combine the waste plastics into HMA, the material first is processed by grinding the waste materials into a powder. The plastic powder is then chemically treated with hydro-peroxide, or modified by maleation by adding maleic anhydride to improve the bonding between the polymers and the asphalt binder (Colbert 2012; Daly et al. 2002). Multiple studies have concluded improved tensile strength, permanent deformation resistance, rutting resistance, low temperature cracking resistance, and age hardening of asphalt mixtures as a direct result from adding waste plastic materials to the HMA mixtures (Zhen et al. 2018; Colbert 2012; Daly et al. 2002). Zhen et al. 2018, who completed a study on adding waste plastic material to high RAP percentage mixtures states: "The results indicated that the samples containing RAP and PET (Polyethylene Terephthalate) derived additives provided better overall performance compared to the conventional binder, increasing the rutting resistance by at least 15% and fatigue cracking resistance by up to 60%. Usage of such waste PET based additives as an additive for RAP mixtures represents an approach to deal with a relevant recycling problem while simultaneously recovering two value-added materials" (Zhen et al. 2018).

2.4 Summary of Findings and Research Gaps

This chapter provided a review of literature relevant to the research presented in this thesis. The findings validated many uses of infrared heating for asphalt pavement construction and repairs including patch repairs, longitudinal crack repairs, joint heating, and full roadway rehabilitation. Multiple studies concluded that heated materials within the hot joint provide greater compaction results, higher density, and fewer air voids resulting in a higher quality repair when compared to cold joints.

Four case studies were reviewed involving infrared heating usage in asphalt pavement crack repairs, airfield pavement repairs, and longitudinal joint construction. All four studies exhibited improved field performance when incorporating infrared heating into their respective pavement maintenance processes. Further long term monitoring of infrared heating projects is recommended in order to create a more comprehensive understanding of the long term effects associated with this method.

In Canada, the use of RAP materials in HMA has gained widespread acceptance, but limited research has been completed on developing asphalt mixtures with over 50% RAP, and no published research was discovered on 100% RAP mixtures. Specialized mix designs for typical patching and infrared heating operations are uncommon, only standard HMA designs or cold mix asphalts are currently used.

Significant research has been completed on additional additives and rejuvenating agents which could be utilized within a 100% RAP patching mixture including crumb rubber, roofing shingles, waste plastics, and fibre reinforcement. These materials will be considered when creating additional 100% RAP mixtures after mix designs using traditional asphalt and petroleum emulsion style rejuvenators are tested.

CHAPTER 3

COMPARISON OF INFRARED HEATING ALTERNATIVES

This chapter will focus on comparing the performance of infrared heating technology to other currently used crack and pothole repair methods.

3.1 Current Repair Methods

According to Uzarowski et al. (2011), the most commonly used crack repair methods are:

1. Crack Sealing, including Routing
2. Crack / Pothole Filling
3. Milling and Repaving

These methods are well known and established repair methods and are used frequently to repair cracking and potholes across the country. Their performance will be examined in this section before being compared to the quality of infrared heating repairs.

3.1.1 Crack Sealing and Routing

Crack sealing is a repair method generally used on smaller, low severity cracks in order to prevent water and incompressible materials from entering the crack therefore slowing propagation of the repaired crack (Decker 2016). Crack sealing is often applied to “working” or “active” cracks, which means they exhibit greater than 2.5mm of movement per year (Transportation Alberta 2003). Working cracks are typically transverse cracks, which are perpendicular to the pavement’s centreline. Crack sealing maintenance is performed by first cleaning the crack using compressed air, ensuring the crack is dry, and clear of any loose pavement fragments or debris. If the crack is not sufficiently dry, a hot air lance can be used to sufficiently dry the inside of the crack. The hot air lance also slightly heats the inside of the crack, making the sealant bond better to the warmed asphalt. These hot air lances, however, are not common practice (Decker 2016). Next, the crack is filled with a hot rubberized high modulus crack filling material. Figure 3.1 below shows the crack sealing process.

Figure 3.1: Left – Crack Cleaning With Compressed Air (Decker 2016), Centre – Hot Air Lance (Al-Qadi, Imad L Ozer et al. 2016), Right – Crack Sealant Application (AsphaltPro 2019)

For crack sealing operations, the timing of application is critical for optimal performance. In the winter and summer months asphalt pavement surfaces expand and contract the most. If sealant is applied during the winter when the crack is at its widest, the sealant will bulge out of the crack during the summer when the pavement compresses. If the sealant is applied in the heat of the summer, the sealant undergoes high tension in the winter and tears, ruining the effectiveness of the seal. When the sealant is applied in the intermediary seasons, the seal is most effective and produces a longer service life (INDOT 2017). Figure 3.2 below demonstrates this concept.

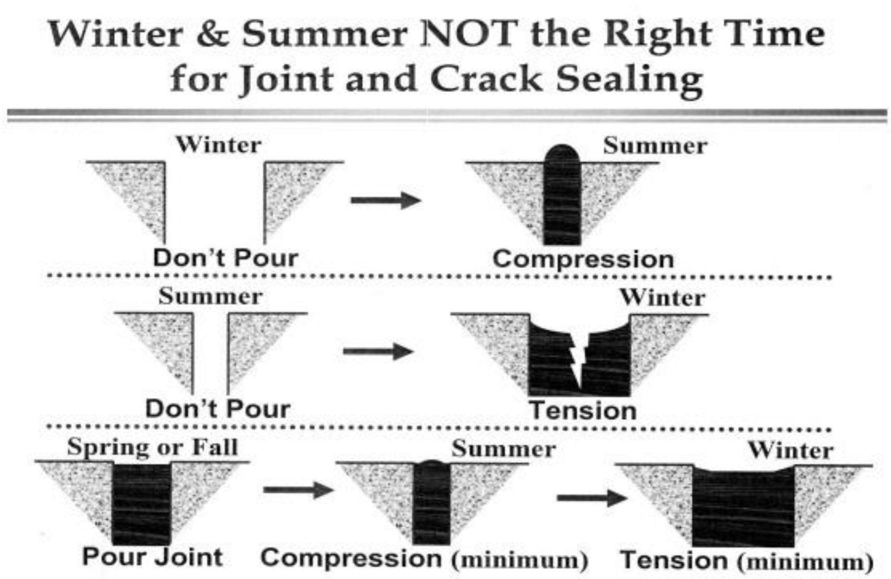


Figure 3.2: Demonstration of Proper Seasons to Apply Crack Sealant (INDOT 2017)

Crack routing is an additional step in the crack sealing method that can be used to create a more effective repair. Crack routing occurs after the crack cleaning process and consists of a routing machine drilling open the crack making it wider and deeper (typically ½” by ½”) (Brahney 2015). A routing machine in use and the resultant routed crack are displayed in Figure 3.3 below.

Figure 3.3: Left – Crack Routing Machine in Use, Right – Routed Crack (Brahney 2015)

Crack routing creates a defined reservoir to contain the applied sealant, allowing the sealant to bond properly with the walls of the crack. During the winter months when the crack is at its widest, the reservoir has already accommodated for the expansion, keeping the crack sealed. Crack routing is only recommend for smaller cracks (smaller than 1” by 1”) and pavement areas with lower crack density (less than 20%), otherwise the pavement area will only be susceptible to further damage from the routing process (Lombardo 2017).

3.1.1.1 Advantages and Disadvantages

Crack sealing is a quick, low cost, crack repair method, typically costing about $8 per linear metre (David Jeong et al. 2015). It is a frequently used repair technique worldwide, so any contractor that works in pavement preservation will have the skills, tools, and machinery to complete a crack sealing repair efficiently. Several technological advances in the field of crack sealing repairs such as using hot air lances and routing machines, have significantly improved the efficiency of these repairs.

Crack sealing is limited to repairing only small pavement deficiencies, as it will not be effective in slowing down the propagation of larger cracks (Lombardo 2017). Crack sealing is also only considered a short-term or preventative repair method. It is useful in preventing small cracks from propagating, but does not remove the deficiency (Uzarowski et al. 2011). This corresponds to a high frequency of continual maintenance required when using crack sealing, which adds up over time when considering the life cycle cost of the pavement.

3.1.2 Crack / Pothole Filling

Pavement areas with more significant cracks or potholes will often be treated with small area patching. "Not active" or "non-working" cracks, cracks which undergo less than 2.5mm of movement per year, are generally treated in this manner as opposed to crack sealing (Decker 2016). In most cases, longitudinal cracks are non-working cracks.

The crack filling repair process again begins with the cleaning of the affected area, making sure the crack or pothole is dry and cleared of any debris. The voids are then filled with a hot or cold virgin asphalt mixture, and compacted into place. Figure 3.4 and 3.5 below display two different potholes being repaired and compacted.

Figure 3.4: Hot Mix Asphalt Pothole Repair Using Plate Tamper for Compaction (City of Edmonton 2019)

Figure 3.5: Pothole Repair Using Cold Mix Asphalt and Hand Tamper for Compaction (EZ Street Asphalt 2019)

For the best quality of repair, the asphalt must be properly compacted into place using a manual plate tamper as shown in Figure 3.4, or some kind of vehicle drum compactor. Common practice often involves only using a hand tamper like shown in Figure 3.5, or simply driving over the filled pothole with a heavy vehicle. These styles of compaction will not create an adequate seal between the virgin material and the in place pavement, resulting in poor performance of the patch (Wilson and Romine 1993).

Hot mix asphalt generally performs much better then cold mix asphalt applications when applied to small area patching. Cold mix asphalt has higher void content then hot mix asphalt, making the patched area more permeable and therefore much more susceptible to damage (Munyagi 2006). Cold mix asphalt will most commonly be used during the winter months when hot mix asphalt cannot be kept sufficiently heated during its cooling process, significantly reducing its structural integrity. Although cold mix asphalt generally has a lower service life then a hot mix patching mixture, it can be used as a temporary patch in winter where a defect is a safety concern. Other benefits of choosing cold mix asphalt over hot mix include lower cost, less construction time, and environmental benefits from huge reduction of energy use between the two mixtures (Munyagi 2006).

3.1.2.1 Advantages and Disadvantages

Small patch repair of asphalt pavement using hot or cold mix virgin materials is another fast, relatively inexpensive maintenance strategy. The main factor in determining the cost of a patching project is the amount of material required to fill the voids. A standard patch filling project will cost $50-$80 per cubic foot of patching material (Wilson and Romine 1993).

There are many different methods of crack and pothole filling, all of which the materials, labour, and equipment are easy to come by. The varying success of these different methods of patching, however, is cause for concern. A low quality cold mix asphalt patch won't last much longer than three months, depending on roadway and weather conditions, while some high quality pothole patching operations can survive a few years without cause for concern (Wilson and Romine 1993). Clients should be specific on what kind of repair they want when hiring a contractor for small patch repairs in order to receive a product with the lifespan they require.

Realistically, this kind of asphalt filling repair is only feasible on small areas of pavement. If a much larger area of pavement is deteriorated and in need of repair, it would be more prudent to use a more thorough repair strategy.

3.1.3 Milling and Repaving

When cracks and potholes are more extensive and/or severe, the affected area of asphalt needs to be completely renewed. The most common method used to achieve complete replacement of a pavement section is milling and repaving. This process starts with using a milling machine to remove the top layer of asphalt to a specified depth, without disturbing the granular base or subbase layers. The removed layer of asphalt is shipped offsite and often stockpiled as RAP. The underlying surface is then cleared of debris and dried. Next, a thin tack coat consisting of emulsified asphalt or PG graded binder is often applied on the milled base to promote bonding between the old and new pavement layers (Munyagi 2006). An asphalt paver will then apply a fresh layer of asphalt pavement, followed by a drum roller style compactor. Figure 3.6 and 3.7 below displays the process of mill and replace.

Figure 3.6: Left – Asphalt Milling Machine, Right – Milled Surface (Cleaver 2016)

Figure 3.7: Left – Application of Tack Coat (Pavement Interactive 2019b), Right – Paving and Compaction (Fowler Construction 2019)

As shown in the above figures, mill and replace operations are commonly completed across an entire lane width. Milling machinery is also manufactured thin enough to only remove individual cracks from the roadway surface. Depending on the size of the opening, these milled crevices can be repaved or simply filled and compacted in a similar manner to crack filling operations.

Unlike crack routing and sealing, or crack filling, this operation removes the entire deficiency out of the pavement, replacing it with virgin materials.

3.1.3.1 Advantages and Disadvantages

The main advantage mill and replace provides is a very high quality of repair. With the entire surface course removed and replaced, all deficiencies are eliminated and a long service life is expected until further maintenance is required. A service life of 10-25 years is expected from an asphalt mill and replace maintenance repair, but this is extremely dependant on the site conditions including traffic, weather, granular base and subgrade performance (Juhasz and Williamson 2017).

This high quality of repair has a high price associated with it. For a crack repair style of mill and replace, $15-$20 per linear metre is a conservative price quote (Uzarowski et al. 2011), while the full lane width mill and replace can cost upwards of $82 per metre squared (Alberta Transportation 2019). This method is significantly more expensive than the other repair methods discussed, but is a long-term solution providing the affected area with a brand new surface course instead of filling and patching continuously propagating defects (Uzarowski et al. 2011). This repair method also requires a long time to complete, so corresponding user costs are high as well. The negative environmental impact associated with this repair strategy is very large, since an entire new surface course is manufactured for the roadway without using any of the in-place materials.

3.2 Infrared Heating

Infrared heating machinery has been manufactured into different devices varying in shape and size specializing in different types of crack and pothole repairs. The most commonly used type of infrared machinery is used for patch style repairs where an area of pavement is heated in place by infrared heaters, scarified with rejuvenators added, then compacted to ensure a thermal bond secures the patch in place. These asphalt patching machines vary in size from small, hand operated machines heating areas of 20” by 51” to larger models required to be towed by a bobcat or skid steer, heating up full lane width areas of 16.6’ by 6.6’ (Heat Design Equipment Inc. 2019). Figure 3.8 below shows two of these infrared patching machines.

Figure 3.8: Infrared Heating Patchers. Left – 8.6’ by 6.6’, Right – 20” by 51” (Heat Design Equipment Inc. 2019)

Infrared heating machinery has many useful repair applications including patching, longitudinal crack repairs, joint heating, and full laneway rehabilitation.

3.2.1 Other Asphalt Heating Techniques

When asphalt is heated without using infrared heating machinery, a conventional flame is most often used. Using a flame to heat asphalt tends to overheat the top layer of asphalt, burning and damaging the asphalt material. Burnt asphalt will not perform well because most of the innate oils will have burned off and the aggregates will be weakened. In place materials heated by a conventional flame burner are not usually heated enough near the bottom of the desired heated section before burning of the top layer occurs. These under heated materials fail to become sufficiently malleable and do not mix properly with added rejuvenators, or create a sufficient thermal bond with connecting asphalt sections (Ding, Huang, and Shu 2016). In comparison, infrared heating is much more reliable to evenly heat the pavement layer to the specified depth with a much lower risk of burning the materials.

3.2.2 Infrared Repair on Site Evaluations

Infrared heating has been proven to provide a quality repair, but since it is a relatively new technique, questioning on the longevity of the repair is common when not provided with much evidence supporting its lifespan. This section investigates multiple locations where infrared heating repairs have been applied, from a freshly repaired site to an eleven year old patch, to observe the condition of infrared heating repairs over time. All of the observed infrared repairs in this section are located within the Kitchener/Waterloo region, so climactic conditions experienced by each patch are generally consistent. All of the patches are also located in high volume commercial parking lots, so relatively similar loading patterns can be assumed for each location.

The first site observed was a restaurant parking lot shared with a Tim Horton's drive through located at 384 King Street North, Waterloo. This location had a working history with infrared heating repairs, and has implemented annual infrared patch repairs for the past couple of years targeted at repairing the most deteriorated areas of the parking lot causing the greatest safety hazards for users. Figure 3.9 and 3.10 below display one brand new infrared heating patch and an area surrounding a storm drain with a two year old infrared patch, marked for further repairs this year. The repaired areas are outlined in yellow.

Figure 3.9: Fresh Infrared Heating Patch Repair

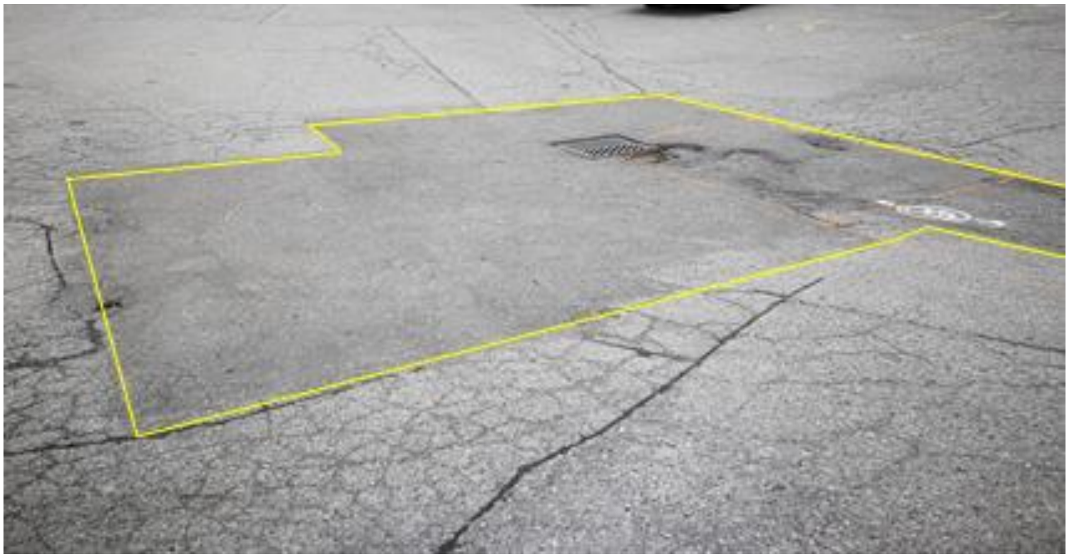


Figure 3.10: Storm Drain Region with Two Year Old Patch Marked for Repair

As illustrated in the above image, pavement infrastructure surrounding storm drains and manholes can deteriorate quickly due to increased stress on the pavement structure. The infrared heating process can repair the deficiencies surrounding the static infrastructure easily without risk of damaging it, but as Figure 3.10 shows, may not provide as long lasting a repair as desired. A study completed in Kitchener on using infrared heating to regrade manholes concluded that the infrared heating process provided a quick, economical, and sustainable repair for this kind of project (Love 2018).

The second site visited was the parking lot of a Wholesale club located at 24 Forwell Creek Road, Waterloo. This site had several previous infrared repairs completed, including patches surrounding storm drains. Figure 3.11 on the next page displays a one, two, three, and four year old patch.

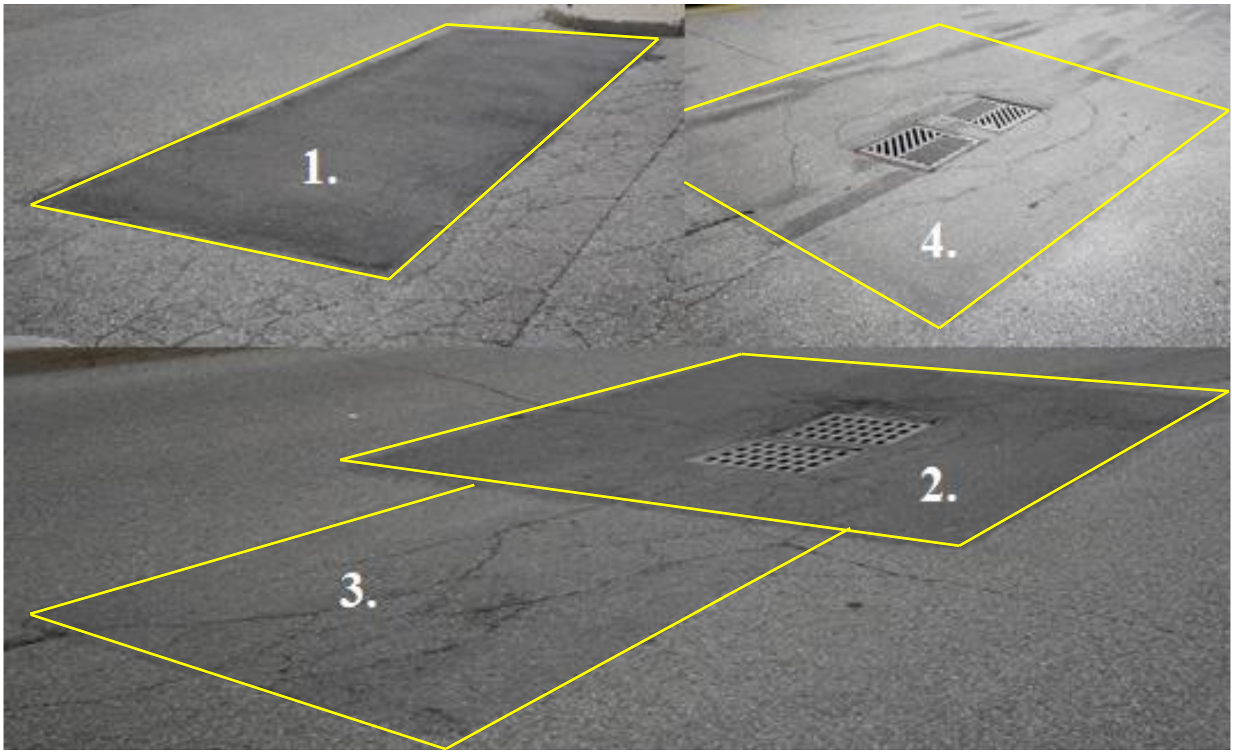


Figure 3.11: One, Two, Three, and Four Year Old Infrared Patch Repairs (As Labelled)

These patch repairs display the most deterioration at the areas surrounding the storm drains, similar to the first site's performance. The three and four year old patches did show signs of deterioration from some small cracks throughout. It should be observed that many of these cracks appear to have propagated into the repaired area from the surrounding pavement, and the edges of the patched areas display minimal cracking, a sign that the thermal bond has performed well.

The final site studied was at the Sunrise Shopping Centre parking lot located on Ottawa Street South in Kitchener. This site contains many different infrared heating patch repairs, some up to eleven years old. Figure 3.12 below shows some of the patched areas observed on longitudinal joint regions, ranging from five to seven years old.

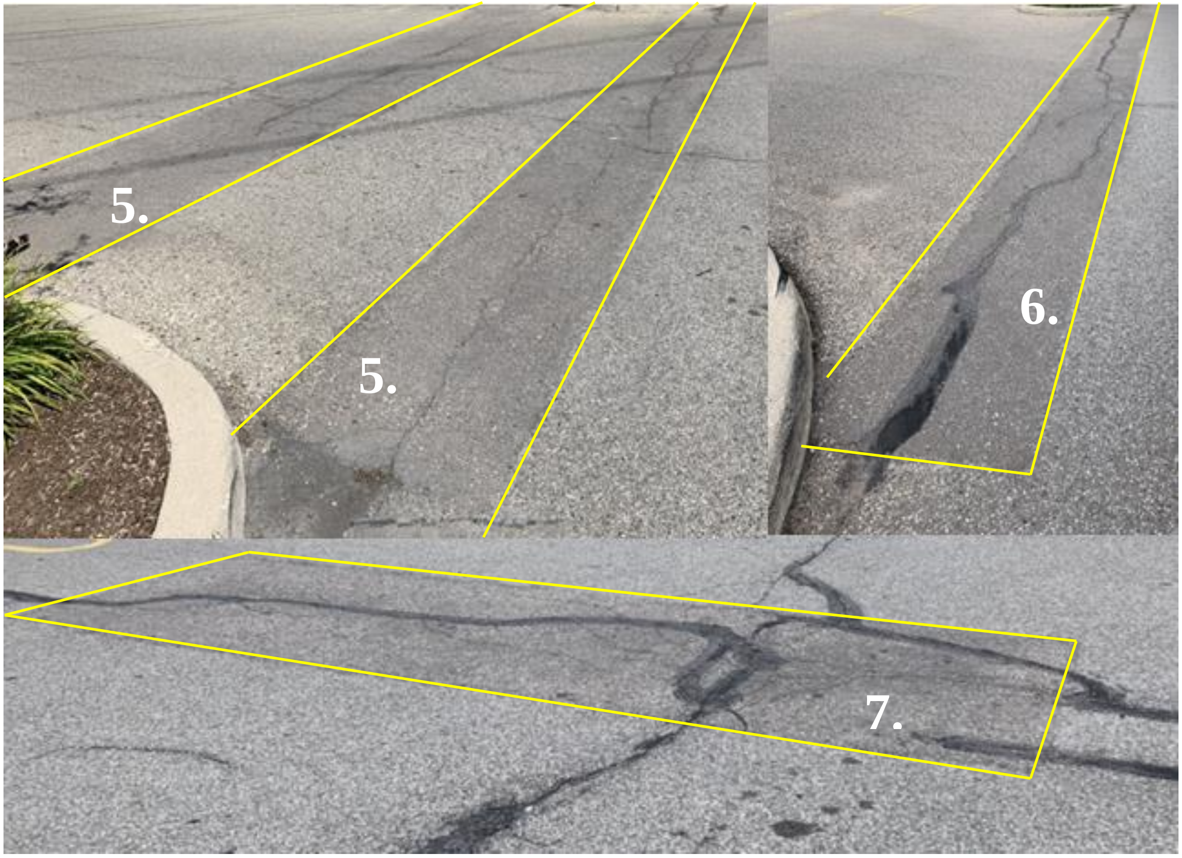


Figure 3.12: Five, Six and Seven Year Old Longitudinal Joint Infrared Patch Repairs (As Labelled)

The five year old patches displayed minor cracking along the longitudinal joints, mirroring the deficiencies originally repaired. The existing pavement structure is unknown, but if the original cracking occurred throughout the entire pavement depth, it is possible old cracking from the original pavement structure reflected up to cause this premature cracking. The six and seven year old patches have had crack sealant applied to some of the larger cracks which propagated throughout. The infrared patches themselves do appear to have held up along the patching joints, but the cracking throughout was deemed severe enough to require crack sealing maintenance. The oldest infrared patches observed at this site were nine to eleven years old, pictures of which are displayed in Figure 3.13 below.

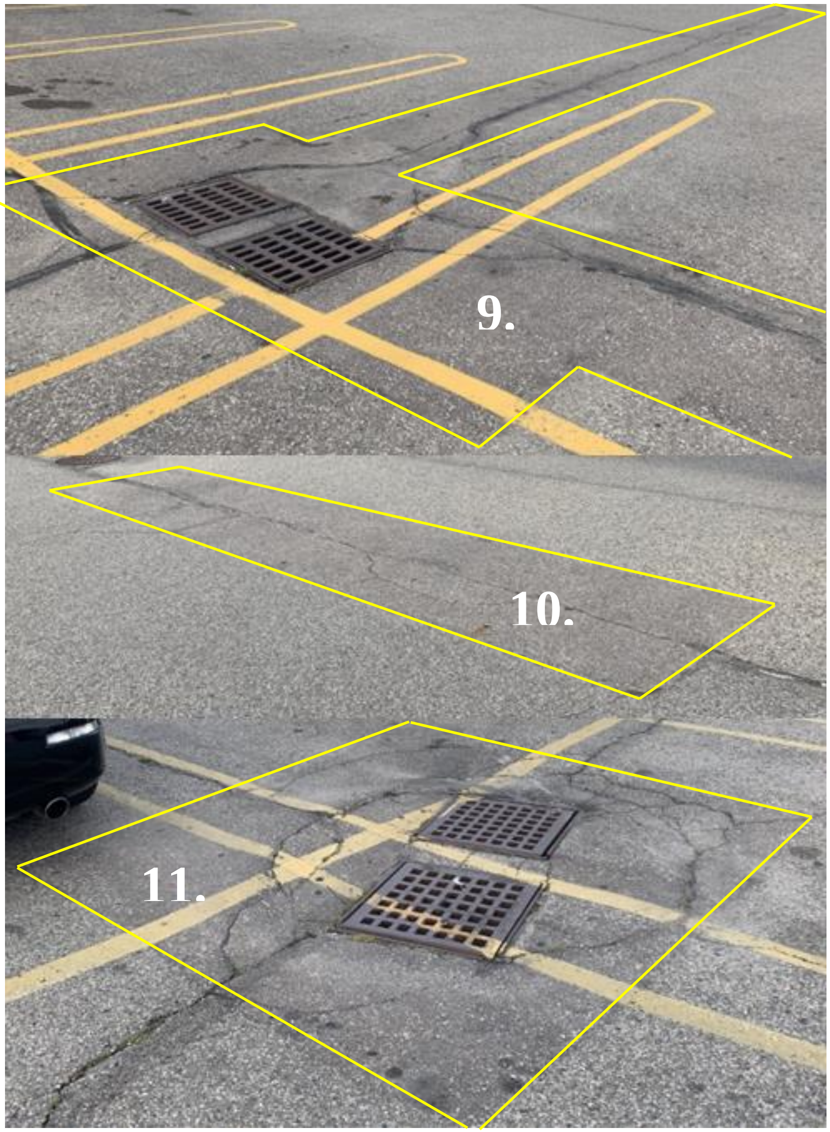


Figure 3.13: Nine, Ten and Eleven Year Old Longitudinal Joint Infrared Patch Repairs (As Labelled)

The nine year old patch is performing well, with crack sealant having been previously applied to some of the cracking which propagated around the drains. The ten year old patch exhibits only minor cracking along the longitudinal joint it lies on. The oldest patch observed at this site was eleven years old, and is exhibiting moderate cracking around the storm drains it is around.

Like any other repair method, the longevity of the repair is very project dependent. Factors including condition of surrounding pavement, climatic effects, quality of repair installment, and traffic loading all greatly affect the longevity of any repair. When comparing the quality of the infrared patches studied, some patches required maintenance only a few years after installation, while most patches displayed adequate performance over the course of their respective lifespans. When comparing the five and ten year old longitudinal joint patches displayed in Figures 3.12 and 3.13, similar minor cracking was observed, impressive results for the older patch, but performance of these longitudinal joint patches is highly dependent on the activity of the longitudinal cracks they are positioned on. All patches observed consistently achieved long lasting repairs around the perimeter of the patches, which cannot be said in general for asphalt milling patch jobs.

3.2.3 Advantages and Disadvantages

When compared to more common crack and pothole repair methods, several performance benefits of the infrared heating method can be observed. Cracks repaired via infrared heating tend to last longer without further deterioration than the other methods mainly because of the thermal bond created between the repaired/rejuvenated area and the surrounding pavement (Davis 2019). This thermal bond is created because both the repaired area and the pavement surrounding that area are heated when the joint between them is compacted. Compared to the cold joint created when using the more commonly used methods, the thermal bond will not allow any water or debris into the joint, increasing the service life of the pavement. Service lives of infrared heating repairs have been observed to last over 13 years (Uzarowski et al. 2011). The cost on infrared heating repairs is more expensive than typical crack sealing and crack filling operations, but can typically be competitive with mill and replacement prices, averaging around $53.28 per square metre for patch repairs, and $17 per linear metre for crack repairs (Heat Design Equipment Inc. 2019). Infrared heating is also an extremely versatile repair technique, similar to mill and replace this method can fix any pavement deficiency within each specific machine's size limitations. Compared to crack sealing and filling, which are not very useful against surface cracking and deterioration such as alligator cracking, infrared heating is of greater value for general usage. Infrared heating is also very flexible when it comes to winter repair options, its heating area is more limited, but it still provides the same quality of repair in any season, unlike crack sealing and filling options which provide a lower quality of repair when not applied in the proper season.

The main disadvantage of infrared heating pavement repairs, and any other new methods in the field, is the lack of availability of machinery and expertise. If a project is not located near an infrared heating contractor, the machinery and trained labour would have to be transported a longer distance to the construction site, dramatically increasing the cost and environmental impact of that option.

3.3 Summary and Comparison

Many factors are considered when determining what repair strategy to use for a specific project, including repair size, time available or budgeted for repair, accessibility /ease of access to repair method, initial cost, and expected frequency between requiring a similar repair. Table 1 below displays these major decision factors most companies focus on when determining what repair strategy to use.

Table 3.1: Comparison of Treatment Alternatives for Crack/Pothole Repairs on Asphalt Pavements

Criteria	Crack Sealing	Crack Filling	Asphalt Milling and Replacement	Infrared Heating
Crack/Pothole Size to Repair	Small Cracks	Small – Medium Cracks / Areas	Large Cracks / Large Areas	Small-Large Cracks / Areas
Repair Time	Very low	Very low	High	Low
Availability	High	High	High	Low
Initial Cost	$8 per linear metre	$50-$80 per cubic foot of patching material	$15-$20 per linear metre, $82 per square metre	$17 per linear metre, $53 per square metre
Maintenance & Rehabilitation Frequency	0.5-5 years	0.5-5 years	10-25 years	5-13+ years

Based on the above table, one can select the most appropriate repair method for a specific project. For small repair projects, one might stick to crack sealing or filling due to their low cost and high accessibility, however, for pavement sections causing continual problems infrared heating repairs should be considered because it provides a longer term solution resulting in less overall life-cycle maintenance costs, with minimal repair times. For larger pavement deficiencies where asphalt milling and replacement is required due to poor materials, infrared heating equipment should still be considered as part of the repair process to provide a hot joint between the existing and patched pavement areas.

CHAPTER 4

CASE STUDY: SUGARBUSH DRIVE

This chapter summarises the progress of an ongoing project between CPATT, the City of Waterloo, and Heat Design Equipment Inc. (HDE) involving the repair of a small residential street.

4.1 Background

Sugarbush Drive is a residential cul-de-sac within the Colonial Acres area at the northern end of the City of Waterloo. Figure 4.1 below displays a map of its exact location.

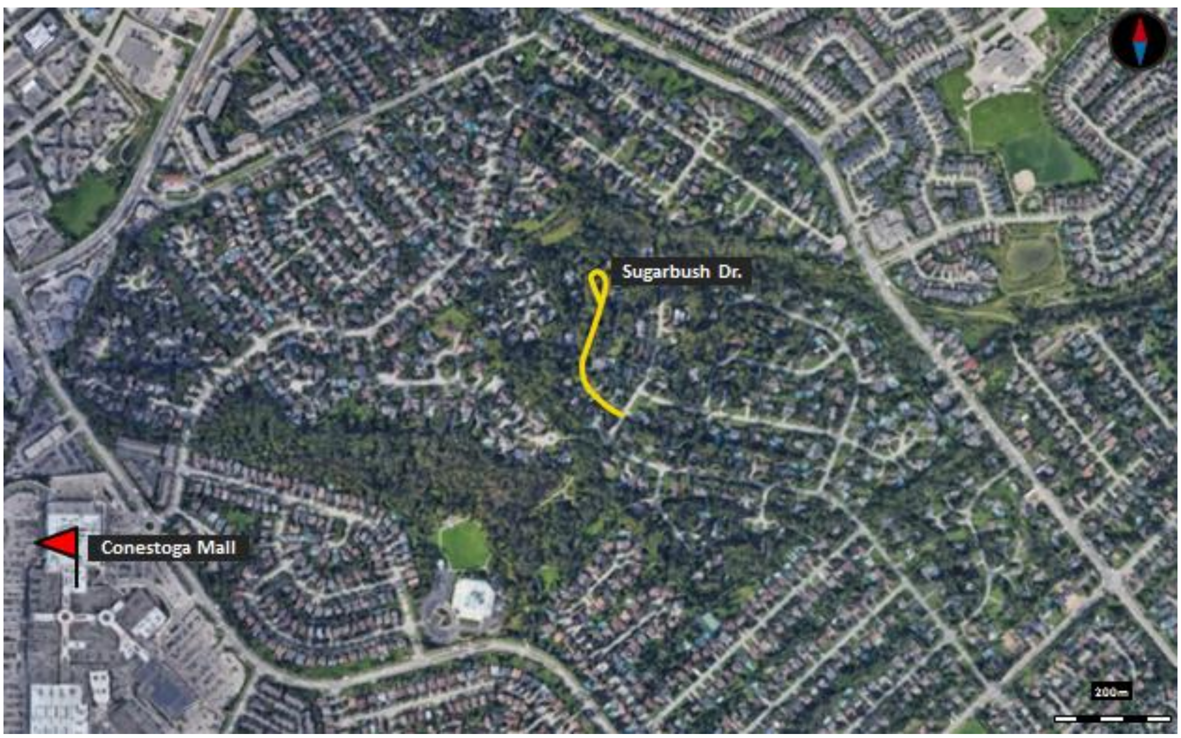


Figure 4.1: Map of Sugarbush Drive (Google Earth 2019)

Sugarbush Drive is approximately 350 metres long and is located within the area bounded by Bridge St., Northfield Dr., Davenport Rd., and Lexington Rd. This residential area of Waterloo is older than most, and does not contain any sidewalk, curb, or gutter details. Residents of this street have been complaining about the deteriorating condition of their street to the City of

Waterloo for a long time, noting in particular the large number of potholes. The City of Waterloo was interested in exploring new pavement repair techniques for the repair of Sugarbush Drive and contacted CPATT to propose a partnership for this project. CPATT decided to consult with HDE on this project and invited them on a site visit to determine some possible repair strategies for Sugarbush Drive.

4.2 Site Condition

A preliminary site visit on May 8th, 2019 was conducted by the author and Daniel Pickel of CPATT, joined by Bob Kieswetter and Nathan Love of HDE. The purpose of this visit was to access the current condition of Sugarbush Drive by performing a visual inspection of the roadway, and to consult with HDE about possible repair solutions involving infrared heating.

Based on the visual inspection, the pavement structure appeared to consist of a 40 mm surface course of asphalt pavement on a granular base. The thickness of the granular base and the nature of the subgrade could not be determined from visual inspection. The pavement surface is crowned at its center allowing minimal drainage; however, the edges of the roadway sit at a lower elevation then the adjacent residential lots. No drainage system was observed. Figure 4.2 below displays a typical street view of Sugarbush Drive.

Figure 4.2: Typical layout of Sugarbush Drive, Taken May 8th, 2019

Various pavement distresses were present throughout the entire length of Sugarbush Drive and, to a lesser extent, throughout the rest of the Colonial Acres neighbourhood. These distresses included many potholes, extensive block cracking, and some pavement distortion along the street edges. Figures 4.3, 4.4, and 4.5 below display some of these features.

Figure 4.3: Potholes and Cracking Around Curve in Sugarbush Drive, Taken May 8th, 2019

Figure 4.4: Block Cracking, Potholes, and Drainage Issues, Taken May 8th, 2019

Figure 4.5: Pavement Distortion Along Sides of Sugarbush Drive, Taken May 8th, 2019

There was evidence of several previous repairs on Sugarbush Drive, including many spot repairs of potholes with both cold-patch and hot mix asphalt. Some larger areas had been saw-cut and filled with hot mix material. The level of effectiveness of these repairs was variable, most likely due in part to their respective ages. Figures 4.6 and 4.7 below display images of some of these repaired sections.

Figure 4.6: Patched Areas of Sugarbush Drive, Taken May 8th, 2019

Figure 4.7: Saw-Cut and Repaired Area, Taken May 8th, 2019

4.3 Proposed Solutions

After the site visit, CPATT collaborated with HDE to propose four different repair options for Sugarbush Drive to the City of Waterloo. These repair options increase in cost and repair quality, three options include infrared heating technology and one does not.

4.3.1 Tier #1 Option

The first proposed option was focused on repairing the most severe distresses on Sugarbush Drive. It was proposed to use infrared heating technology to repair the major pavement distresses which were most noticeably affecting ride quality; specifically the larger potholes and severe block cracking which residents were complaining about the most. Given the estimated pavement depth of 40mm to 50mm, infrared heating would easily be able to heat the in-situ asphalt material to full depth in order to rework the asphalt to remove deficiencies and fully integrate the repaired asphalt to the adjacent pavement. A similar patching methodology could be applied to the rest of the Colonial Acres neighbourhood where further severe distresses exist.

Simply patching the most severe deficiencies would be the least expensive maintenance strategy. It would quickly fix the most severe distresses on Sugarbush Drive and the surrounding neighbourhood. This option also has the least amount of commitment from the City of Waterloo to the new infrared heating repair technique, while still providing the City with a good opportunity to examine the performance and access the quality of infrared heating repairs on its roadways.

Sugarbush Drive, however, is severely damaged throughout its entire length. It would be difficult to narrow down the most distressed places to just a few to complete repairs on. This could cause additional complaints to the city if some residents didn't get the areas repaired that they wished. On the other hand, if all the areas which are in need of spot repairs were patched, the majority of Sugarbush Drive would be repaired in the proposed manner. At that point, it would be more practical to repair the entire roadway at once like one of the tier 2 through 4 options suggest.

If Sugarbush Drive was to be spot repaired in the manner tier 1 suggests, the repair may not necessarily last as long as infrared heating repairs are predicted to. Since Sugarbush Drive is already so deteriorated, there are not many areas with asphalt pavement in good enough condition for the repair to properly bond to. If a repaired section of asphalt is next to cracked and deteriorated pavement, those deficiencies will quickly spread and the repaired area will not be effective as long as it should. With the current state of Sugarbush Drive, areas which would not be repaired under the tier 1 option would not last much longer until they create severe defects which will require further maintenance and repair in the near future. With these conditions, tier 1 is simply not a long term solution for the City of Waterloo.

Tier 1 does not address the drainage issues Sugarbush Drive is experiencing, so the pavement surface will continue to deteriorate at an accelerated rate. The excess of water on the roadway after rainfall events will continue to cause safety concerns for users.

4.3.2 Tier #2 Option

The second rehabilitation option would consist of repairing the entire surface area of Sugarbush Drive using infrared heating. A large, full lane width infrared heating train would be constructed by HDE for this project. This would work similarly to the infrared heating train created for longitudinal cracking repairs discussed in section 2.1.1.2, except it would be as wide as the entire road, shorter in length, and move much slower. This machine would heat the entire width of Sugarbush Drive simultaneously, and would be followed by a mechanical scarifying unit that would break apart and mix the heated asphalt materials to achieve uniformity. Additional HMA material could be added to the roadway in places where significant material loss occurred to bring the road up to a reasonable grade. Rejuvenating admixtures would be applied to the heated asphalt in order to restore ductility and cohesion to the RAP material. The heated and rejuvenated material could then be graded to a suitable profile before it is compacted. This process should result in a pavement structure equivalent to the initial design, with an asphalt thickness of 40mm to 50mm.

Using this method would repair the entire length of Sugarbush Drive using only in-place and RAP materials. Using only recycled asphalt materials significantly decreases the carbon footprint when compared to a conventional road resurfacing project. This option is also a relatively fast repair, estimated to take only one day to complete. A quicker repair results in lower labour costs and less disruption of the operation of Sugarbush Drive, which in turn reduces the associated user costs. A complete and uniformed repair of Sugarbush Drive will result in longer lasting roadway structure than tier 1 would provide. Sugarbush Drive would uniformly age and not require additional repairs for a long time.

The tier 2 option would provide an excellent opportunity for the City of Waterloo to examine the effects a full infrared heating repair has on a roadway. When partnered with CPATT for this project, there is also a price reduction for the city associated with the research partnership. This provides more incentive for the City to choose a more rigorous repair option when they have the opportunity. The City in turn receives valuable information from the university regarding the performance of the repair.

A disadvantage of this second option is its lack of impact on the granular base course. Unlike conventional mill and replace operations, infrared heating does not expose the granular base layer. If it was exposed contractors would be able to inspect it, regrade any sections if necessary, and compact it. Often a primecoat is applied to a granular base before asphalt pavement is installed on top of it. This primecoat stabilizes the fine particles in the granular base to preserve the materials, fills the surface voids to protect the granular base from moisture penetration, and creates a stronger bond between the granular base and applied asphalt layer (ISHAI and Livneh 1984). None of this base course refurbishment would occur with the tier 2 option. Secondly, the in place pavement material on Sugarbush Drive is very old and in rough shape. The original asphalt concrete may not conform to the higher quality standards we have for asphalt today. Even with the asphalt scarified and rejuvenators added, lower quality asphalt is not likely to perform as well over time. With this option a proper grade will be restored to Sugarbush Drive, however, the roadway will still be at a much lower elevation compared to the adjacent lots. This lack of proper drainage will continue to adversely affect the performance of Sugarbush Drive. Finally, the second option would be a more expensive repair than tier 1. Working within the City's budget for the project always has to be considered, otherwise other areas of distress may not receive the repairs they need.

This remediation technique would be recommended throughout the Colonial Acres neighbourhood in areas exhibiting similar distresses to Sugarbush Drive. It is expected these areas will continue to degrade rapidly in the next few years, and will soon fall into the same state of disrepair as Sugarbush Drive. It would be preferable to repair these roadways before they reach such a state, so less in place material is lost, and residents are more comfortable.

4.3.3 Tier #3 Option

The third option would build onto tier 2. After the roadway is resurfaced using infrared heating, a lift of virgin hot mix asphalt could be installed on top to further raise the grade of Sugarbush Drive. A tack coat would be applied to the in place asphalt repaired by infrared heating to the new asphalt layer in order secure a proper bond between the two layers. The paving crew could directly follow the infrared heating team, as the heated asphalt would bond to the new asphalt well. The heating, scarifying, and addition of rejuvenators would produce a great base asphalt layer to support a top course. The repaired base layer would resist reflective cracking from transferring to the surface course, unlike the existing pavement in its current condition.

By adding an additional layer of asphalt, this tier 3 option produces an even stronger pavement structure. If the City of Waterloo wants to explore infrared repairs but is unsure about committing to a solution relying on this method completely, the tier 3 option provides that. Considering the drainage quality, the higher elevation of the roadway with the additional asphalt layer would provide some additional assistance in reducing damage to the roadway cause by moisture.

On the other hand, this option requires hiring multiple contractors, and much more equipment for a relatively small job, increasing the cost of tier 3 substantially. This option produces a very thorough repair, but it may be excessive considering the level of service required for Sugarbush Drive.

4.3.4 Tier #4 Option

The final proposed repair option would not use infrared heating technology; instead, a full-depth reclamation and reconstruction of Sugarbush Drive would be completed using virgin materials. It would be strongly recommended that the roadway's elevation be substantially raised for this repair option to improve drainage of the area and reduce long term damage to the new roadway.

Advantages of this option include a long service life of the new road and familiarity with the construction processes. This final option, however, would be the most expensive and not take advantage of the research opportunity using infrared heating technology provides. The City of Waterloo would not retain the financial benefits a research partnership with CPATT provides if they don't use infrared heating.

4.4 Sugarbush Drive Testing

Following the site visit, it was decided to complete a series of laboratory tests in order to further understand the current state and composition of Sugarbush Drive before determining what type of repair to proceed with. These tests were performed on site at Sugarbush Drive and in the CPATT laboratory, the results and testing procedures of which are summarized in the following section.

- Lightweight Deflectometer Testing

- Asphalt Binder Extractions
- Gradation Testing
- Proctor Testing

4.4.1 Lightweight Deflectometer Testing

On May 30th, 2019, Sugarbush Drive was tested using a Dynatest Keros Prima 100 portable falling weight deflectometer (FWD), or lightweight deflectometer (LWD). This device was used to measure the pavement's deflection when impacted by the weighted device. Figure 4.8 below shows the LWD in use.

Figure 4.8: Lightweight Deflectometer Testing at Location #3 on Sugarbush Drive, Taken May 30th, 2019

Fourteen different locations were tested along Sugarbush Drive, with 2-5 repetitions at each point. These locations were evenly distributed along the entire length of Sugarbush Drive, and varied in roadway profile position as well. Test location 1 is located at the south end of Sugarbush Drive, and the sequential test locations move north up the street to locations 12, 13, and 14 located within the cul-de-sac. Figure 4.9 below displays the locations of all the LWD testing sites.

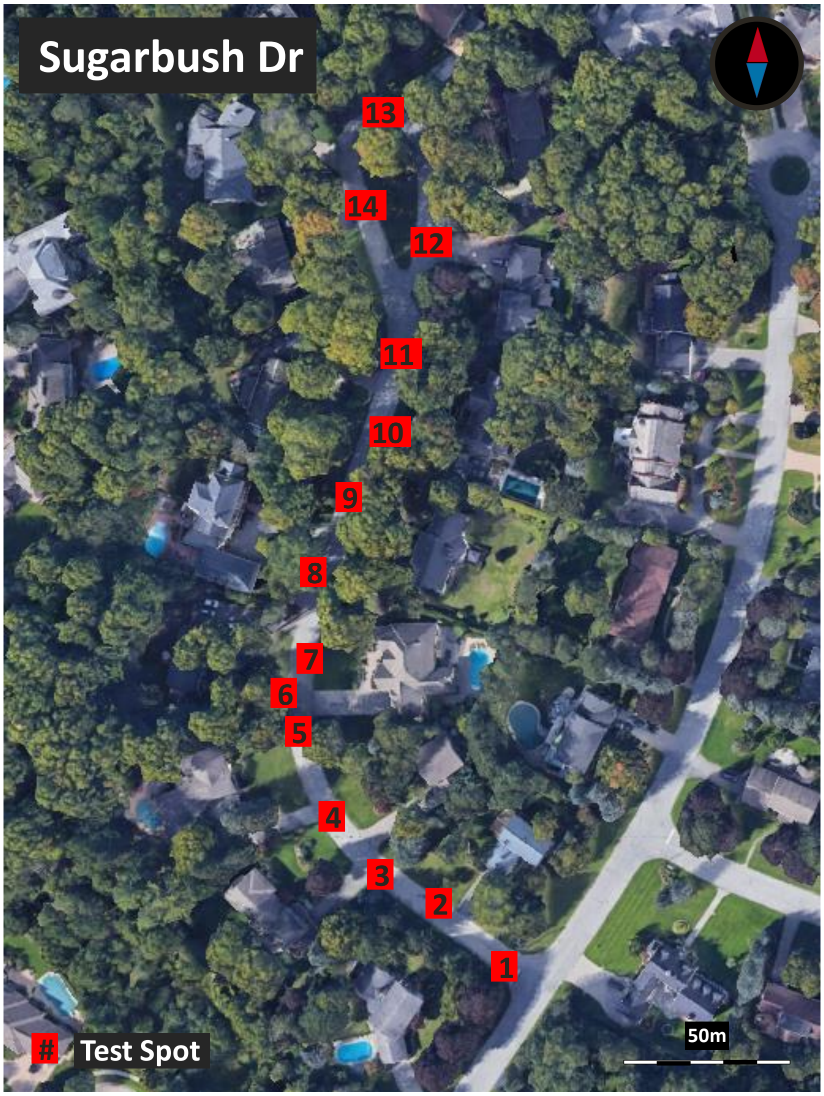


Figure 4.9: Lightweight Deflectometer Testing on Sugarbush Drive (Google Earth 2019)

The average deflection measured across Sugarbush Drive was 321 microns. Figure 4.10 below displays the deflection values retrieved from Sugarbush Drive.

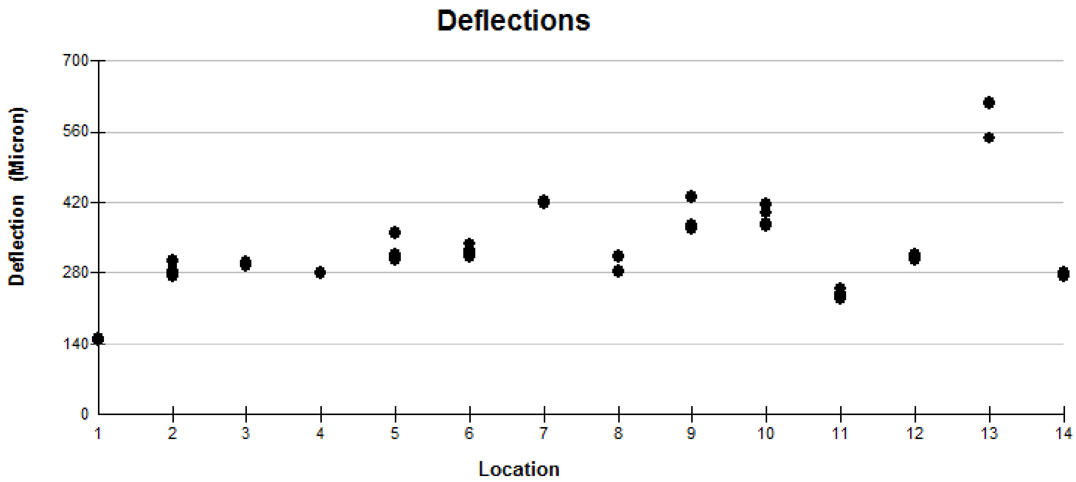


Figure 4.10: Deflections on Sugarbush Drive

From these deflection values, the surface deflection moduli were calculated using Boussinesq's theory for an elastic half-space, while assuming a rigid plate (Equation 1 below).

$$E = \frac{\pi(1-v^2)r\sigma_0}{2d_1} \tag{1}$$

Where:

- E = material modulus (MPa);
- v = Poisson's ratio (assumed to be 0.35);
- r = radius of the LWD loading plate (150 mm);
- σ_0 = maximum applied stress (kPa); and
- d_1 = maximum deflection under the plate center (μm).

The average surface deflection moduli calculated for Sugarbush Drive was 280 MPa. Figure 4.11 below displays the surface deflection moduli for all locations tested.

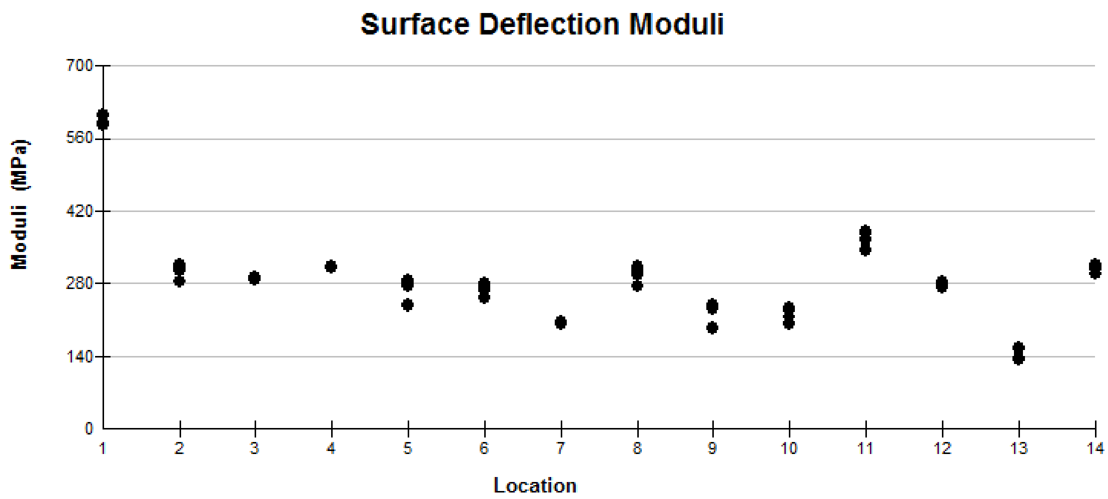


Figure 4.11: Surface Deflection Moduli on Sugarbush Drive

The testing indicates that the pavement throughout Sugarbush Dr. has a relatively consistent structural capacity. The two outliers which were noted were at Locations 1 and 13. Location 1 was at the intersection of Grant Crescent and Sugarbush Drive and the relatively high modulus may indicate a pavement built-up design at an intersection, or more recent construction on Grant Cres. Location 13 was located at the furthest extent of Sugarbush Dr. in the cul-de-sac portion of the street. This location (shown in Figure 4.12 below) showed severe degradation and standing water adjacent to the testing location. It is suggested that this portion of the street have more significant rehabilitation in order to address the apparent drainage problems and resulting low structural stiffness.

Figure 4.12: Testing Location 13 on Sugarbush Drive, Taken May 30th, 2019

4.4.2 Borehole Testing

In order to understand the physical properties of the roadway, its constituent materials have to be tested. With of the lack of information the City of Waterloo had on the composition of Sugarbush Drive, it was necessary to complete borehole testing to observe and retrieve samples of all components of the roadway structure. These samples were tested in order to identify the current composition and condition of Sugarbush Drive. This section of the report summarizes the procedures and results from the extraction of the materials through the laboratory testing completed on the asphalt cores, granular base, and subbase materials.

4.4.2.1 Borehole Extractions

On the same date as the lightweight deflectometer testing (May 30th, 2019), the City of Waterloo hired contractor WOOD PLC to extract 6 borehole samples, 5 of which granular base and soil subgrade samples were drilled for and extracted as well. Four of the drilling locations were located on Sugarbush Drive, while two were located on nearby Whitmore Drive. Figure 4.13 below displays a map of the colonial acres neighbourhood indicating the locations of Sugarbush Drive, Whitmore Drive, and all the borehole testing locations.

Figure 4.13: Site Overview (Google Earth 2019)

The samples retrieved from Whitmore Drive were to act as a baseline when comparing the condition of Sugarbush Drive to the average condition of the rest of the Colonial Acres neighbourhood. Retrieving some data from the surrounding neighbourhood is prudent for planning future maintenance and repairs. Figure 4.14 below displays in more detail the locations borehole samples were extracted on Sugarbush Drive.

Figure 4.14: Sugarbush Drive Borehole Locations and Identifications (Google Earth 2019)

On Sugarbush Drive, boreholes BH19-1 through BH19-4 were retrieved from areas of pavement showing different levels of degradation, and spaced evenly throughout the length of the street. At locations BH19-1, BH19-3, and BH19-4 an asphalt core was retrieved along with granular base and subgrade materials samples. At location BH19-2, only an asphalt core sample was retrieved. The original intention of only retrieving a core at this location was to sample the material from a large patch on the Eastern side of the road. The contractor, however, misinterpreted the instructions and took the asphalt core sample from the West side of the road, removing an asphalt core sample of the original pavement structure. The BH19-2 asphalt core sample was still a useful sample and data point, but information on the quality of that asphalt patch was not retrieved as planned.

The two borehole sites on Whitmore Drive were labelled BH19-5 and BH19-6. Asphalt core samples as well as granular base and soil subgrade samples were retrieved from these locations. The locations of these borehole sites are displayed in Figure 4.15 below.

Figure 4.15: Whitmore Drive Borehole Locations and Identifications (Google Earth 2019)

The asphalt core samples were retrieved using an 8 inch diameter electric asphalt coring drill. Some samples were retrieved as whole cylinders but most were split and in multiple pieces due to cracking. Figure 4.16 and 4.17 below show the recovery of the asphalt core sample BH19-1.

Figure 4.16: Borehole Site BH19-1 on Sugarbush Drive, Taken May 30th, 2019

Figure 4.17: Left – Drilling Asphalt Core BH19-1, Right – Retrieving Asphalt Core BH19-1, Taken May 30th, 2019

After the asphalt core was removed, the granular base samples were retrieved using an auger. Since the thickness of the granular base layer was unknown, the auger was regularly removed and cleared of material until the subgrade was observed. Granular base materials and the subgrade materials were separated as much as possible and collected for testing. The thickness of the granular base layer was noted for each borehole site. Figure 4.18 below displays the auger drilling for materials.

Figure 4.18: Auger Drilling on Sugarbush Drive, Taken May 30th, 2019

A copy of the original field report by WOOD PLC from May 30th, 2019 is located in Appendix A.

4.4.2.1.1 Field Results

This section summarizes the information obtained visually from the borehole extractions on May 30th, 2019 before any laboratory tests were completed.

4.4.2.1.1.1 Asphalt Cores

The average thickness of each asphalt core sample was measured to determine the depth of the asphalt surface course layer in each location. All borehole samples with surface cracking crossing the core split as soon as they were retrieved, indicating all cracking penetrates the entirety of the asphalt surface course. Figure 4.19 below displays core samples BH19-3 and BH19-4. Tables 4.1 and 4.2 show the thickness of all asphalt cores retrieved.

Figure 4.19: Asphalt Core Sample BH19-3 (Left) and BH19-4 (Right)

Table 4.1: Asphalt Core Thicknesses Sugarbush Drive

Core ID	Thickness (mm)
BH19-1	60
BH19-2	75
BH19-3	75
BH19-4	90
Average	75

Table 4.2: Asphalt Core Thicknesses Whitmore Drive

Core ID	Thickness (mm)
BH19-5	60
BH19-6	75
Average	67.5

These measurements indicate on average a much thicker asphalt surface course (75 mm) then originally estimated (40 mm) from viewing the depth of several potholes on Sugarbush Drive.

This depth is still reasonable for infrared heating technology to sufficiently heat Sugarbush Drive to full depth, however, thicker asphalt regions such as location BH19-4 would require more heating time, with extra care taken not to overheat the surface materials.

4.4.2.1.1.2 Granular Base Layer Thicknesses

Measurements collected at each borehole location indicating the approximate depth of the granular base layer are summarized in Tables 4.3 and 4.4 below.

Table 4.3: Granular Base Layer Thicknesses Sugarbush Drive

Location ID	Thickness (mm)
BH19-1	220
BH19-3	245
BH19-4	245
Average	236.7

Table 4.4: Granular Base Layer Thicknesses Whitmore Drive

Location ID	Thickness (mm)
BH19-5	340
BH19-6	255
Average	297.5

4.4.2.2 Laboratory Testing

The following laboratory testing procedures were completed to further understand the current state and composition of Sugarbush Drive:

- Asphalt Binder Extractions
- Gradation Testing
- Proctor Testing

The following section describes the testing procedures used, and summarizes the results. Original laboratory data from all tests performed is located in Appendix A.

4.4.2.2.1 Asphalt Binder Extractions

Extraction testing was completed on the sampled asphalt cores in the CPATT laboratory in order to discover the current asphalt binder content of the in-place materials on Sugarbush Drive. The extractions were performed following AASHTO designation T 164-11 (Same as ASTM D 2172-05) using method A (Centrifuge extraction).

The asphalt cores were first heated until malleable then were split into two samples. Based on the observed nominal maximum aggregate size of 9.5mm within the sample (excluding the outside edge cut aggregate), the sample sizes were all a minimum mass of 1000 grams, with most samples ranging in weight from 1000g to1200g. The samples were inserted into the large centrifuge and soaked with methylene chloride, a solvent which separated the binder from the aggregate. The centrifuge spins to remove the liquid methylene chloride with the binder. This process is repeated until the binder is sufficiently separated from the sample. The smaller centrifuge is then utilized to remove any fine materials which got separated from the rest of the aggregates in the first centrifuge. Essentially, the binder content is the percentage of weight difference of the sample from before and after the binder was removed. Figure 4.20 below illustrates the extraction process.

Figure 4.20: Left - Sample Separating, Centre – Centrifuge, Right – Fine Materials Centrifuge

Two extractions were performed on each asphalt core, and the asphalt binder content was calculated using equation 2. Table 4.5 and 4.6 below summarize the laboratory test results, displaying the average asphalt binder content per sample by weight percentage.

$$Asphalt\ Binder\ Content\ (\%) = \frac{(W_1 - W_2) - (W_3 + W_4)}{(W_1 - W_2)} \times 100 \qquad (2)$$

Where:

- W_1 = mass of test portion;
- W_2 = mass of water in test portion;
- W_3 = mass of extracted mineral aggregate; and
- W_4 = mass of mineral matter in the extract.

Table 4.5: Asphalt Content of Borehole Samples Sugarbush Drive

Core ID	%AC
BH19-1	7.69
BH19-2	7.05
BH19-3	6.55
BH19-4	7.53
Average	7.21

Table 4.6: Asphalt Content of Borehole Samples Whitmore Drive

Core ID	%AC
BH19-5	8.91
BH19-6	6.51
Average	7.71

The average asphalt contents of Sugarbush and Whitmore drive were tested to be 7.21% and 7.71% respectively. This represents a high asphalt content considering the age and condition of the roadways. It should be noted that because the infrared heating repair technology makes use of the existing asphalt cement in repairs, these high AC values result in better performance from this style of repair.

4.4.2.2.2 Gradation Testing

In order to analyze the composition of the granular and subbase materials, sieve analyses were performed on the collected samples following ASTM standard D 6913. The purpose of the sieve analysis was to determine the percentages of the varying sized grains within a soil sample. This test is constructed to have a combination of sieves ranging from largest sieve size, 37.5 mm, to the smallest sieve, 75 μm. The process to calculate the percent passing through each sieve begins with measuring the initial total weight of the dry sample. After each sieve sorts the material that passes through it from the material it retains, the weight of the contents retained in the sieve is measured. Then the percent's retained and percent's passing are calculated using equations 3 and 4 below.

$$\%\text{Retained} = \frac{\text{Cumulative Weight}}{\text{Initial Total Weight}} \times 100 \tag{3}$$

$$\%\text{Passing} = 100 - \%\text{Retained} \tag{4}$$

The following sections summarize the results of this testing. Appendix A contains individual calculation results for all percent's retained and percent's passing.

4.4.2.2.2.1 Granular Base Materials

Figure 4.21 below displays the gradation graph from the sieve analysis completed on granular base material samples BH19-1, BH19-3, and BH19-4 of Sugarbush Drive, and sample BH19-5 from Whitmore Drive, compared to the OPSS standard specification for granular A and B.

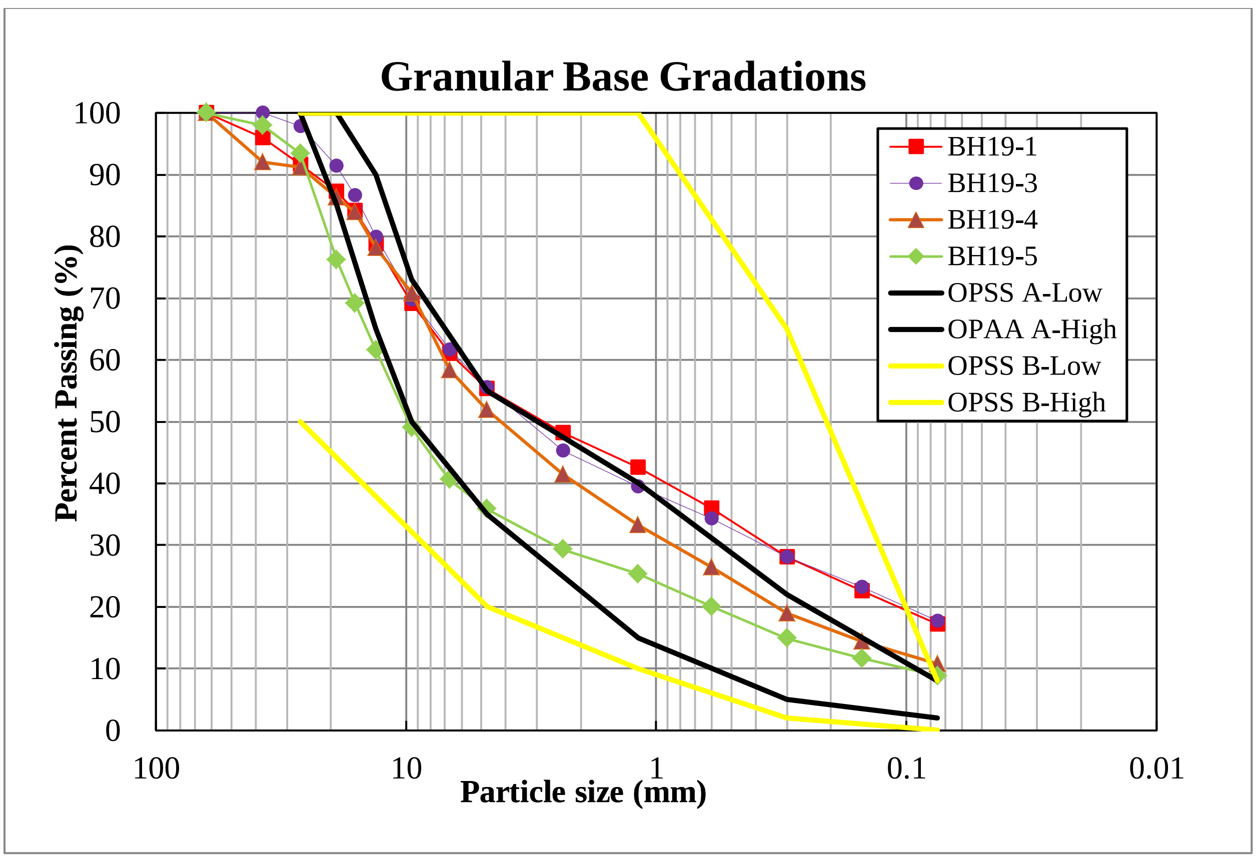


Figure 4.21: Granular Base Gradation Graph

The granular base samples taken from Sugarbush Drive all appear to be uniformly well graded with an average of 45.8% gravel sized material, 39.0% sand, and 15.2% fines. This gradation does not specifically conform to a granular A or B mixture, containing gravel sized particles consistent with granular "A" specifications, but on average more fine materials following a granular "B" composition. Excess fine materials could be a result of some subgrade material getting mixed in with the granular base sample retrieved. Sample BH19-5 retrieved from the nearby Whitmore Drive contains more course material then the Sugarbush Drive samples.

4.4.2.2.2.2 Subgrade Materials

Figure 4.22 below displays the gradation graph from the sieve analysis completed on the subgrade material collected from boreholes BH19-1, BH19-3, and BH19-4 of Sugarbush Drive, and BH19-5 from Whitmore Drive.

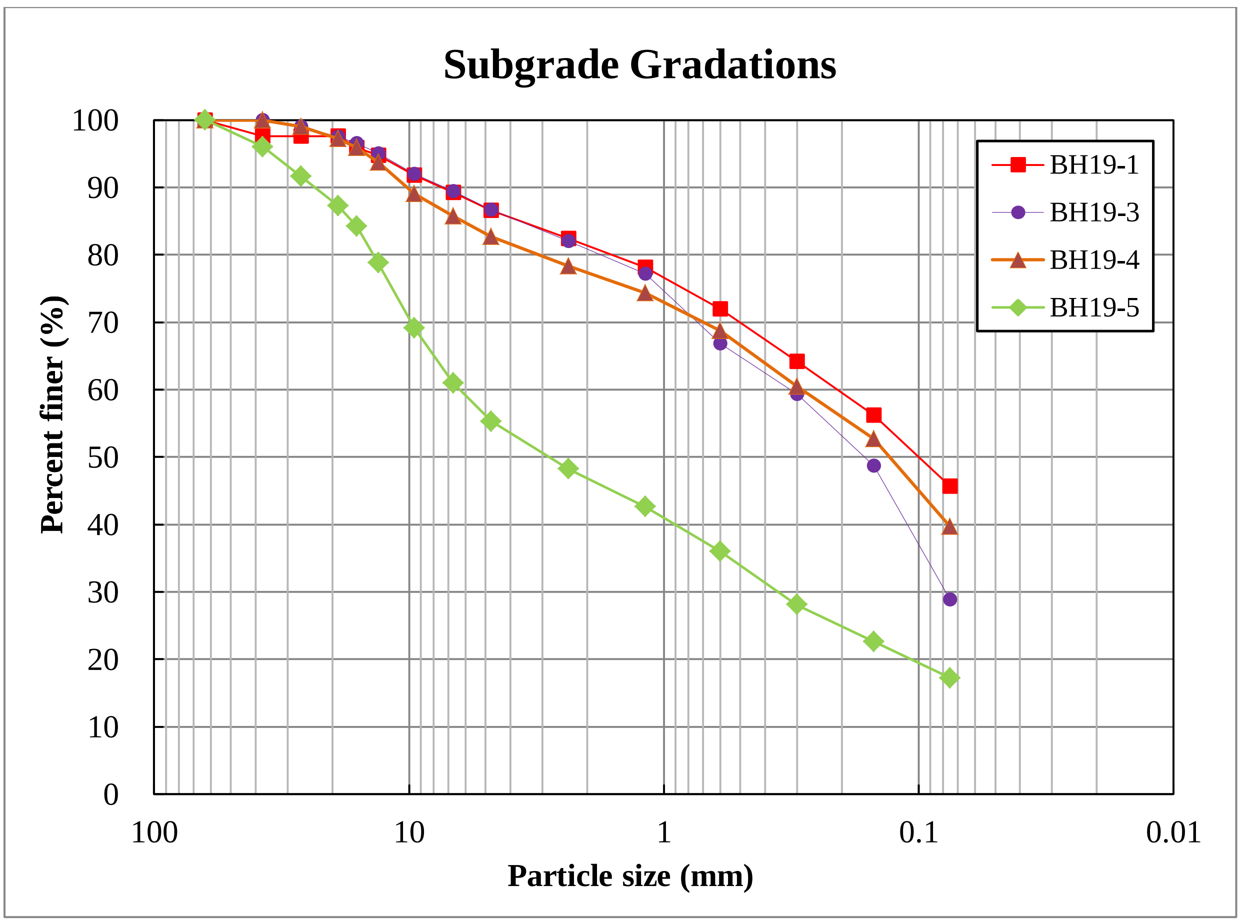


Figure 4.22: Subgrade Gradation Graph

The subgrade gradations indicate a more significant difference between the soils present on Sugarbush and Whitmore Drives. Soil gradations beneath Sugarbush Drive are consistently a course grained sandy mixture with fines, with on average 14.7% gravel, 38.1% fines, and 47.2% sand. The subgrade on Whitmore Drive consists of 44.7% gravel, 17.2% fines, and 38.1% sandy material, also consistent with a course grained material containing sand and fines. The Whitmore Drive subgrade has a significantly higher proportion of large gravel sized material.

4.4.2.2.3 Proctor Testing

A proctor test was completed on two granular base and two subgrade samples using AASHTO standard T99 for standard proctor in order to determine the optimal moisture content for the best compaction of each sample. This test is performed by compacting layers of the soil sample at a predetermined moisture content within a cylindrical mold using a hammer of standardized weight falling from a specified height. Three layers are compacted to create each sample. The compacted sample is weighed and from this information the wet and dry densities of each sample can be calculated using equations 5 and 6 below.

$$Wet\ Density\ \left(\frac{g}{cm^3}\right) = \frac{Wet\ Soil\ Mass\ (g)}{Volume\ of\ Mold\ (cm^3)} \tag{5}$$

$$Dry\ Density\ \left(\frac{g}{cm^3}\right) = \frac{Wet\ Density\ \left(\frac{g}{cm^3}\right)}{100+\%\ Moisture} \times 100\% \tag{6}$$

This process is repeated, increasing the moisture content of the soil sample each iteration until the dry density begins to decrease, indicating optimal dry density and moisture content has been surpassed.

The samples used were from boreholes BH19-3 and BH19-5 one sample taken from each of Sugarbush and Whitmore Drive’s respectively. Subgrade sample BH19-3 was tested with method “A”, which uses a 101.6 mm diameter mold and a 24.5 N rammer dropped from a height of 12 inches. Both granular base samples and subgrade sample BH19-5 were tested with method “C”, which differs from method “A” only by using a larger 152.4 mm diameter mold. The larger mold was used on these samples because they had more course grained gravels in their gradation, and a larger mold provides more accurate results when testing with larger aggregates as the volume of the aggregates is proportionate to the mold size. Figures 4.23 and 4.24 below display the optimal moisture content curves created for each tested sample.

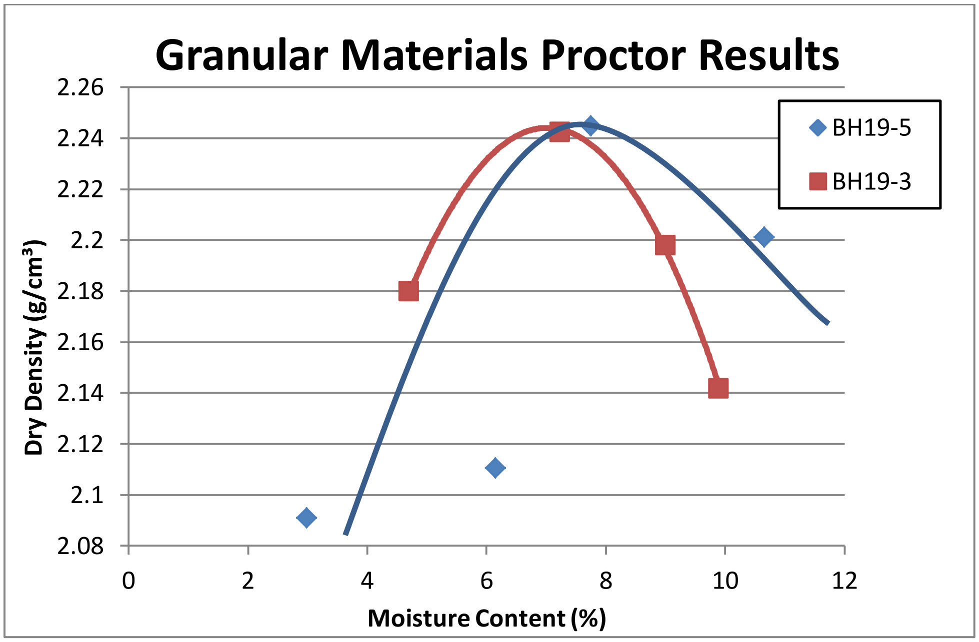


Figure 4.23: Granular Proctor Materials Graph

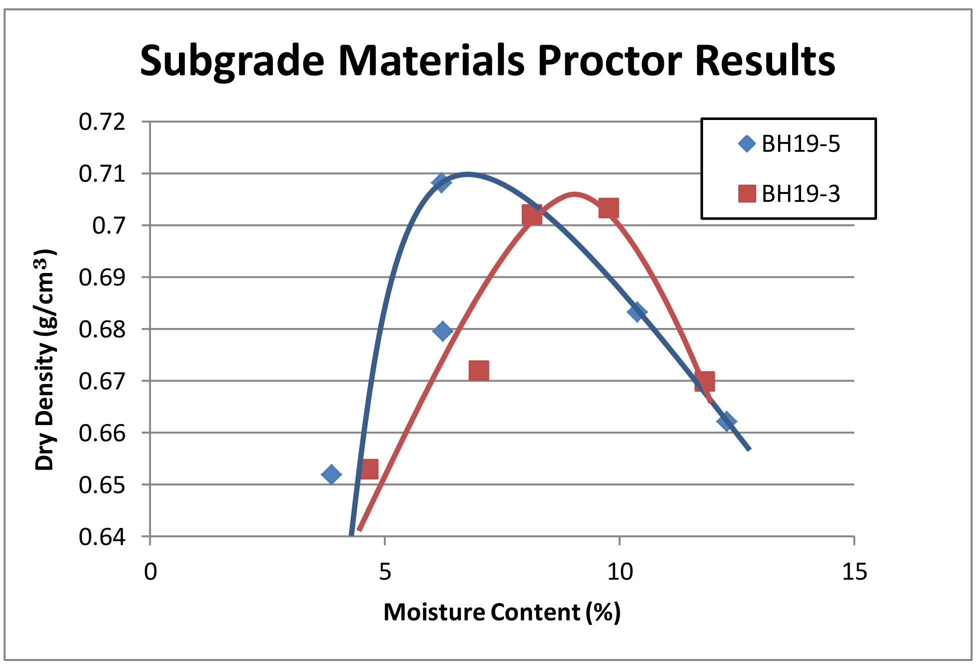


Figure 4.24: Subgrade Proctor Materials Graph

Optimal moisture content for each sample occurs at the apex of the curve, when maximum dry density is achieved. Based on the above graphs, the optimal moisture content for the granular base materials are very similar at 7.5% for BH19-3 and 7.9% for BH19-5. For the subgrade materials, optimal moisture content for sample BH19-3 on Sugarbush Drive is 9.5%, while the subgrade from Whitmore Drive is optimal at a lower 6.0%.

4.5 Summary of Results

Sugarbush Drive is currently in a decrepit state, below the service standards of the City of Waterloo. Figure 4.25 below displays the current condition of Sugarbush Drive, including the properties discovered from laboratory tests completed.

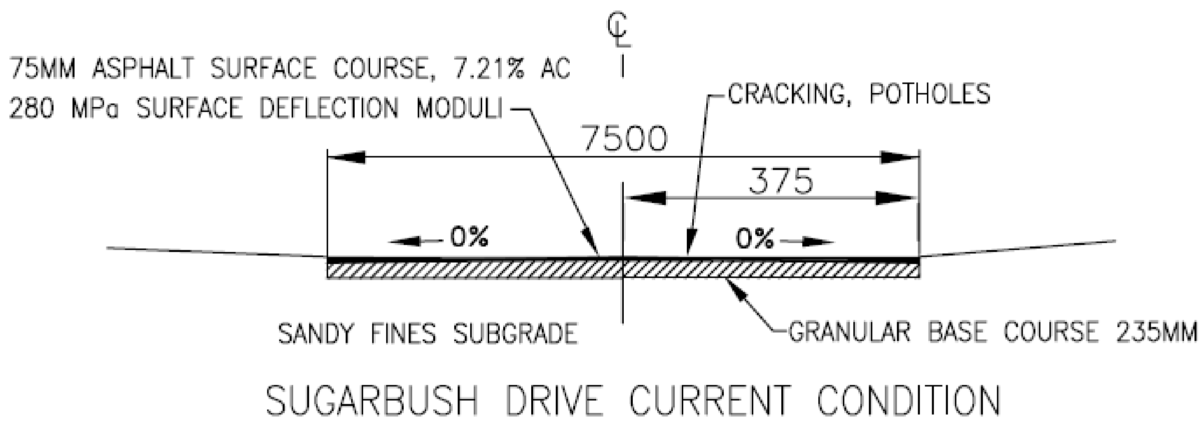


Figure 4.25: Current Sugarbush Drive Cross Section

4.6 Recommendations

Based on the results of laboratory tests completed, Sugarbush Drive has solid granular base and subgrade materials, and an asphalt surface course with high AC content, which makes this site an optimal candidate for infrared heating repairs. Three possible repair alternatives were proposed which involved infrared heating, out of these three, it is recommended to implement the tier 2 solution. This option involves the full surface rehabilitation of Sugarbush Drive using infrared heating, adding new HMA to areas missing asphalt from extensive potholes and cracking, bringing the pavement structure to a uniform grade. To provide improved drainage, the pavement profile will be adjusted accordingly. Figure 4.26 below displays a cross section for the proposed tier 2 solution.

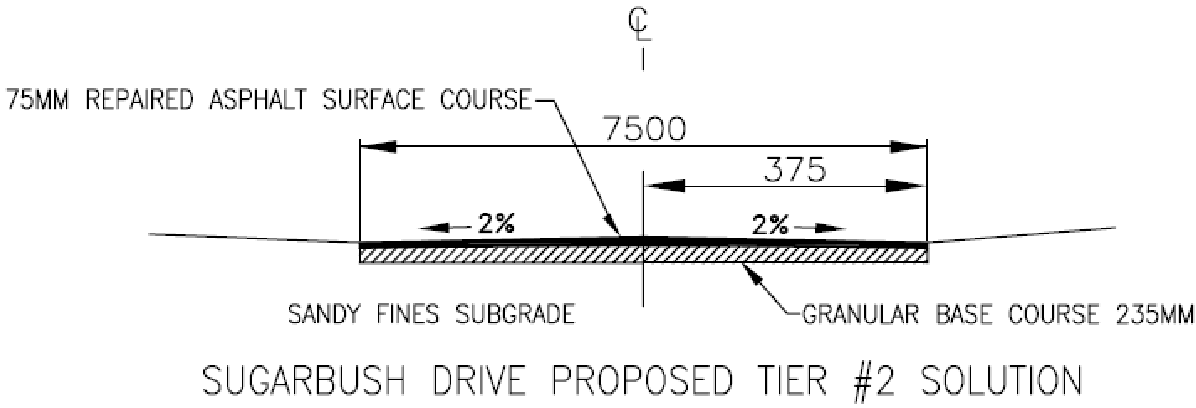


Figure 4.26: Proposed Sugarbush Drive Cross Section

It is recommended to further incorporate recycled materials into this solution by using a 100% RAP mixture as discussed in Chapter 5 to bring the surface course up to grade instead of virgin materials.

Overall, when establishing a new repair method like infrared heating, pilot projects like the Sugarbush Drive project are extremely important. Expanding a company's client base to include large municipalities like the City of Waterloo will provide a wealth of new project opportunities and more importantly, the affirmation of the repair method to other potential clientele.

CHAPTER 5

100% RECYCLED ASPHALT PAVEMENT PATCHING MIXTURE

Chapter five summarizes the progress of the ongoing project CPATT and Heat Design Equipment Inc. are working on involving the creation of a reliable asphalt pavement patching mixture containing as much RAP material as possible.

5.1 Research Objectives

The overall objective of this project is to develop an optimal mix design using 100% RAP and evaluate its performance in pavement preservation and maintenance including crack sealing, filling, milling and patching, and hot in-place recycling. This research project will focus on the following specific objectives:

- Evaluate the current condition of multiple RAP sources based on the properties of extracted binder and aggregate.
- Evaluate the effects of the type and dosage of rejuvenator and heating temperature during the mixing phase.
- Determine the most efficient combination of rejuvenator and infrared heating temperature for RAP in various pavement preservation treatments in accordance with industry specifications and evaluate its laboratory and in-service performance by conducting a series of tests.
- Characterize and compare the RAP properties heated by infrared heating machinery and conventional high intensity burner.
- Develop the optimal mix design using 100% RAP in selected pavement preservation and maintenance and determine the optimal quantity of RAP if virgin materials are needed for certain applications.
- Determine and verify the life-cycle economic and environmental benefits resulting from the proposed mix design.

5.2 Research Methodology

To achieve the objectives of the research indicated in the previous section, a flowchart was made, displayed in Figure 5.1 below.

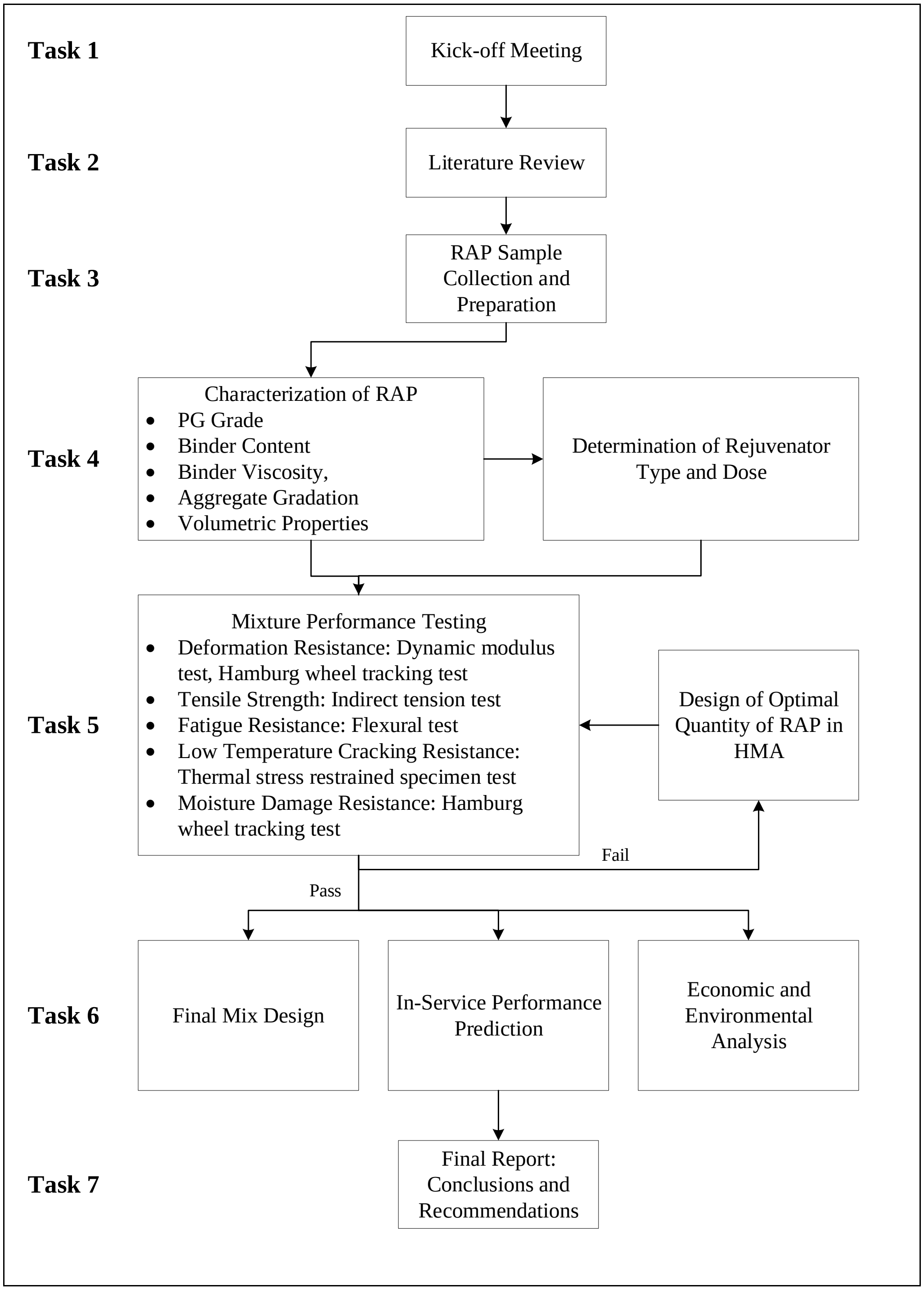


Figure 5.1: Research Methodology

Task 1: This task will engage in a project kick-off meeting with all designated liaison people. The intent is to identify any modifications needed with respect to the tasks and expectations so that both the research team and Heat Design Equipment Inc. have a mutual understanding of the project. During this stage, necessary information to carry out the following tasks will be requested and collected by the research team including specifications of RAP, rejuvenators, infrared heating machinery and potential testing equipment to be used for performance determination.

Task 2: This task will provide a comprehensive literature review on the state-of-the-art of pavement maintenance and preservation treatments using RAP, especially high percentage of RAP in HMA. The heating technologies used in pavement crack repairs and hot in-place recycling will be compared and pavement performances associated with different heating technologies will be reviewed. The current state of knowledge on concepts and approaches related to determine the type and dosage of rejuvenator and the related effects on RAP by various test methods will be reviewed as well. Attention will also be focused on industry specifications, national, provincial and state highway agencies' technical reports, and asphalt pavement associations' practices and publications.

Task 3: This task will involve RAP collection and test sample preparation. Multiple RAP sources that represent different collection methods will be sampled. The consistency of RAP characteristics for each stockpile will be verified with a RAP QC plan. To carry out the following performance tests, RAP will be processed by removing oversized particles, crushing large chunks and screening for multiple size range if necessary.

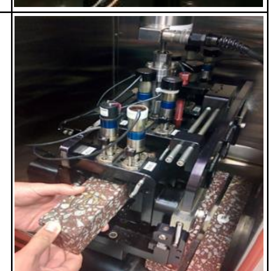
Task 4: This task will focus on the characterization of RAP and the determination of rejuvenator type and dosage in RAP. Characterizing RAP material involves the determination of fundamental RAP properties, which will aid in the selection of rejuvenator and facilitate mix design in Task 5 if virgin materials are needed. The testing procedure to determine the performance grading of the extracted binder will follow the standard specification for performance-graded asphalt binder, AASHTO M 320. First, binder will be extracted from RAP using solvent and a centrifuge according to AASHTO T 164, in which the binder content in percentage will be determined and aggregates will be recovered for gradation. Binder will be further aged based on the protocols for AASHTO T 240, Rolling Thin Film Oven (RTFO). Then a Dynamic Shear Rheometer (DSR) will be used for characterizing the RTFO aged binder rheology (complex shear modulus G* and phase angle δ) according to AASHTO T 314, and a Bending Beam Rheometer (BBR) will also be used to determine the creep stiffness and m-value of the RTFO aged binder according to AASHTO T 313. With the measurements of binder parameters in DSR and BBR, the PG high, intermediate and low temperatures, which represent rutting resistance, fatigue resistance and low temperature cracking resistance respectively, can be determined. When grading asphalt binder, typically rotational viscometer, binder flash point, mass loss, and pressure aging vessel (PAV) performance tests are performed, however, with RAP binder these tests are not necessary because the binder has been previously aged (AASHTO 2018).

There exist a few methods in determining the optimal dosage of rejuvenator to be used in RAP. According to Zaumanis, Mallick and Frank, the relationship between rejuvenator dosage and Performance Grade high, intermediate and low temperatures of extracted binder from RAP is approximately linear (Zaumanis, Mallick, and Frank 2014). Therefore, reference binders with specified PG will be determined first. Then common types of rejuvenator such as aromatic extract, waste engine oil and organic product will be selected. To achieve similar rheological properties as the reference asphalt binders, each source of RAP will be blended with each type of rejuvenator for a range of rejuvenator doses, and rejuvenated binder rheology will be determined by conducting DSR and BBR. From test results, the maximum and minimum required rejuvenator doses will be determined to satisfy each reference binder's PG. Meanwhile, the most suitable type of rejuvenator will be determined for the specific region and application. In addition, other approaches in determining the dosage of rejuvenator in RAP will also be considered, revised and possibly used.

Task 5: This task will be directed at performing comprehensive testing on different 100% RAP mixtures with suitable dosage of rejuvenators heated to different temperatures by a portable infrared heating asphalt recycler. Due to the unique mechanism of infrared heating that cannot be replicated in the lab, a portable infrared heating asphalt recycler will be brought to the University of Waterloo, and all of the different RAP mixtures will be created inside it.

Testing of these mixtures will be performed according to AASHTO M 323 Superpave Mix Design. The performance tests are used to relate laboratory mix designs to accrual field performance, and aims to characterize key indicators including deformation resistance, fatigue resistance, low temperature cracking resistance, tensile strength, stiffness and moisture susceptibility to satisfy national and provincial specifications in Canada. Table 5.1 presents the performance tests used in this research to ensure the satisfactory performance of the RAP mixtures. If the performance of the mix cannot be guaranteed in certain pavement preservation treatments, the quantity of RAP to be blended with virgin materials will be determined according to Sanchez so that a new mix (HMA with RAP) will be designed (Sanchez et al. 2012).

Table 5.1: Performance Tests to be Completed on 100% RAP Patching Mixtures

Test Name	**Performance Indicator**	**Standard**	**Output**	**Test Configuration**
Dynamic Modulus Test	• Deformation resistance • Stiffness	AASHTO T 378	• Dynamic modulus • Aging index • Freeze-thaw durability index	
Flexural Test (Four-point Bending Beam)	• Fatigue resistance	AASHTO TP 8	• Cycles to fail • Shape factor	
Indirect Tension Test	• Tensile strength	AASHTO TP 9	• Creep compliance and strength	

Thermal Stress Restrained Specimen Test (TSRST)	• Low temperature cracking resistance	AASHTO TP 10	• Fracture temperature • Fracture energy	
Hamburg Wheel Tracking Test	• Deformation resistance • Moisture susceptibility	AASHTO T 324	• Rut depth • Shear Upheave • Inflection Point	

Task 6: This task, which involves final mix design determination, in-service performance modeling, and economic and environmental analyses, will be carried out once the results of performance testing are satisfactory from Task 5. The final optimal mix design will be summarized as a guideline including RAP selection, sample preparation, rejuvenator type and dosage selection, designed mixture volumetric property calculations and use of appropriate test methods for mixture performance. The second part of this task is to conduct statistical analysis such as Analysis of Variance (ANOVA) and various statistical tests on the test results from the previous task. Correlations among different variables will be tested and identified, and long-term in-service performance will be predicted by statistical modeling. In addition, sensitivity analysis will be conducted for key variables to evaluate the effects on RAP performance. The last part of this task is to perform economic and environmental analysis, which is essentially a life-cycle assessment on the use of 100% RAP in pavement maintenance and preservation including crack sealing, filling, milling and patching, and hot in-place recycling. Case studies will be used to quantify expenses and greenhouse gas emission over the life cycle stages: raw material acquisition, production, construction, maintenance, and end of service life. Focus will be on comparisons between using infrared heating machinery and conventional gas burner, and comparisons among different percentages of RAP used in the preservation treatments.

Task 7: This task will deliver a final report detailing the design, test methods, results, and analysis of the research, with conclusions, and recommended guidelines for future use. It should be noted that over the course of the project, the research team will interact directly with the industry partner, to whom progress reports both formally and informally will be prepared and submitted.

5.3 Project Progress

At this point task 1 through task 4's characterization of RAP has been completed for this project. During task 1, the project kickoff meeting, three sources of RAP were identified as a base material for the 100% RAP patching mixtures, and four rejuvenator types were selected to form a base matrix of 12 possible patching mixture combinations to be tested. Other rejuvenator alternatives and additives were discussed as viable options for further development of a 100% RAP patching mixture, and the possibility of a secondary phase of this project expanding the scope to specialize in incorporating these methods was discussed. Section 5.4 discusses the different RAP and rejuvenator sources, and the scope of testing in this and possible future projects.

The proposed literature review was completed, information from which is summarized in chapter 2. Chapter 3 of this thesis consisted of the comparison study between infrared heating and several more conventional repair methods.

During task 3, the three different RAP materials were collected from stockpiles at HDE's Kitchener headquarters. The RAP was uniformly processed at HDE prior to retrieval. Enough material for all future planned testing in phase 1 was collected to ensure uniformity between tests, because RAP quality can vary dramatically depending on its age, and site conditions it is collected from. The three RAP sources are further discussed in section 5.4.

Finally, all laboratory testing planned for task 4 was completed on the collected RAP samples, the results and processes of which are described in section 5.5. Future tasks beyond the completed RAP testing and binder characterization, including rejuvenator dosage determination, are not covered in this report.

5.4 Proposed 100% RAP Patching Mixture Materials and Mix Combinations

Three different RAP products which are commonly used and locally available were chosen as the base products for the 100% RAP matching mixtures, they will be referred to as samples A, B, and C respectively:

- Sample A – RAP "Bricks"
- Sample B – Aged Ripoff
- Sample C – Scrapings or milled RAP

Sample A is manufactured RAP bricks made from unused excess asphalt mixes from local asphalt companies. This product is expected to perform the best as it is aged the least out of all the RAP sources. HDE receives these RAP bricks infrequently, and is able to use them in approximately 10% of their patching mixtures. Sample A is stored under an outdoor shelter on a pallet, covered in an additional tarp, and is least exposed to weather conditions as it waits to be used for a project.

Sample B consists of aged ripoff from local municipalities' excess materials. Sample B is the largest source of RAP, with 70% of HDE's RAP coming from this source. This RAP source is stockpiled loose under a sheltered enclosure. The final RAP source, sample C, consists of scrapings and milled RAP materials. This source material is sorted separately from sample B as it is considered to be in worse condition.

Sample C is stored outside sheltered only by a tarp. This source is only used approximately 20% of the time, when no other RAP source is readily available. RAP samples B and C are delivered with no knowledge of the products age, condition, or history. This makes it difficult to be sure all patching mixtures created with the same source of material will perform uniformly. Both samples contain large chunks of material when delivered and are crushed and processed by HDE to uniform size before being added to any mixture. Figure 5.2 below displays some of the RAP sample sources and how they are stored after delivery before use.

Figure 5.2: Left – Sample C Storage, Centre – Sample B Before Processing, Right – Sample B Processed in Storage, Sample A Stored Under Blue Tarp

The following four rejuvenating agents have been selected to be used in the 100% RAP patching mixtures:

- Reclamite
- ARA-3P
- CRF
- Cyclogen M Base Oil

The first rejuvenator, reclamite, is a maltene-based cationic petroleum emulsion manufactured by Tricor Refining, LLC. This product is advertised to decrease the viscosity and DSR values of asphalt binder, as well as restore the asphalt to aggregate bond (Tricor Refining 2019c). Reclamite is spray applied and recommended to be diluted with water prior to application. ARA-3P is a rejuvenating agent manufactured by Ergon Asphalt and Emulsion Inc. This product is composed of 50%-70% water, 20%-40% asphalt binder, and 1%-20% petroleum extract and heavy naphthenic distillate solvent (Ergon Asphalt and Emulsions Inc. 2019).

ARA-3P is produced as small pellets which can be added to as an asphalt mixture as it is being heated, and should be mixed thoroughly and completely dissolved before application.

CRF, also manufactured by Tricor Refining LLC, is an asphalt emulsion. Its primary function is an asphalt restorative seal and crack filler. When diluted with water it can also act as a spray applied rejuvenating agent. This product contains greater than 40% asphalt, less than 35% distillates (petroleum), hydrated heavy naphthenic, and less than 5% proprietary ingredients (Tricor Refining 2019a).

The final product is not a rejuvenator but pure AC provided to HDE by Tricor from excess production. The product is called Cyclogen M, and it was designed with RAP material compatibility in mind (Tricor Refining 2019b)

Other rejuvenator alternatives and additives were considered to incorporate into a 100% RAP patching mixture including crumb rubber, asphalt roofing shingles, fibre reinforcement, and waste plastics. The majority of these products are not properly recycled or reused after their service life, and similarly to RAP are stockpiled or not properly disposed of. To further expand the scope of this project, RAP sources could be combined with these materials to create different patching mixtures. Table 5.2 summarizing the different feasible combinations of RAP and rejuvenator in each phase of the project is displayed below. The purple section of the table represents the initial project's scope, with the green section highlighting possible mix combinations with the expanded project scope discussed.

Table 5.2: 100% RAP Patching Mixture Testing Matrix

RAP \ Rejuvinator	Reclamite	ARA-3P	CRF	Cyclogen M	Crumb Rubber	Asphalt Shingles	Fibre Reinforcement	Waste Plastics
A-Brick	?	?	X*	NA	X	X	X	X
B-Aged Ripoff	X	X	X	X*	X	X	X	X
C-Scrapings	X	X	X	X	X	X	X	X

Where:

- X – Possible combination to be tested;
- X* - Combination used frequently to be tested for validation purposes;
- ? – Unknown combination;

- NA – Combination not possible or not recommended (Not to be tested in this study);
- Purple – Phase 1: Optimal 100% RAP Patching Mix Design and;
- Green – Phase 2: Rejuvenator Alternatives in 100% RAP Patching Mix Project.

HDE has found the most success in the field using CRF rejuvenator with RAP sample A, and the Cyclogen M with RAP B. They know from experience these combinations provide a good patching mixture, but the performance has not been verified by testing. It has been initially determined to not test the mixture combination of RAP sample A with Cyclogen M. The RAP bricks should already contain sufficient AC content, and in combination with the Cyclogen M, the mixture would have too much AC, resulting in a suboptimal mix. Asphalt mixtures which contain an excess of binder typically experience problems such as lower skid resistance, bleeding, increased rutting and shoving.

5.5 Characterization of RAP

In order to determine the properties and PG grade of all three RAP source materials, the following laboratory tests were completed according to their respective AASHTO standard processes:

- Asphalt Binder Extractions
- Rolling Thin Film Oven (RTFO)
- Dynamic Shear Rheometer (DSR)
- Bending Beam Rheometer (BBR)
- Gradation Testing

The following section describes the testing procedures used, and summarizes the results obtained. All raw lab data and original calculations are located in Appendix B.

5.5.1 Binder Extractions

The first test administrated was binder extraction following AASHTO standard T 164. The same process and machinery was used for the Sugarbush Drive project as described in section 4.4.2.2.1. For these binder extractions, regent grade trichloroethylene was used as the solvent in order to not alter the properties of the extracted binder. Table 5.3 below displays the calculated asphalt cement contents of each of the three RAP mixtures by mass percent.

Table 5.3: Asphalt Content of Different RAP Sources

Sample ID	%AC
A	5.97
B	6.05
C	5.40

All three RAP sources tested contained similar binder contents, with sample B containing the highest amount of AC at 6.05%, and sample C containing the least (5.40%). Both samples B and C were expected to contain less AC than sample A because of their higher age and the fact that both were previously used materials.

After the centrifuge binder extraction process, the binder was still mixed with the trichloroethylene. In order to perform further laboratory tests on the extracted asphalt binder, it needs to be separated from the solvent. To separate these two substances a rotary evaporator was used following ASTM standard D 5404. This process involves the distillation of the solvent binder solution. The solution is placed in a heated oil bath and subjected to a partial vacuum with a flow of nitrogen and carbon dioxide gas. The solvent evaporates out of the solution and condensates and is collected in a separate vessel, leaving only asphalt binder in the original container. Figure 5.3 on the following page displays the rotary evaporator utilized in the CPATT lab.

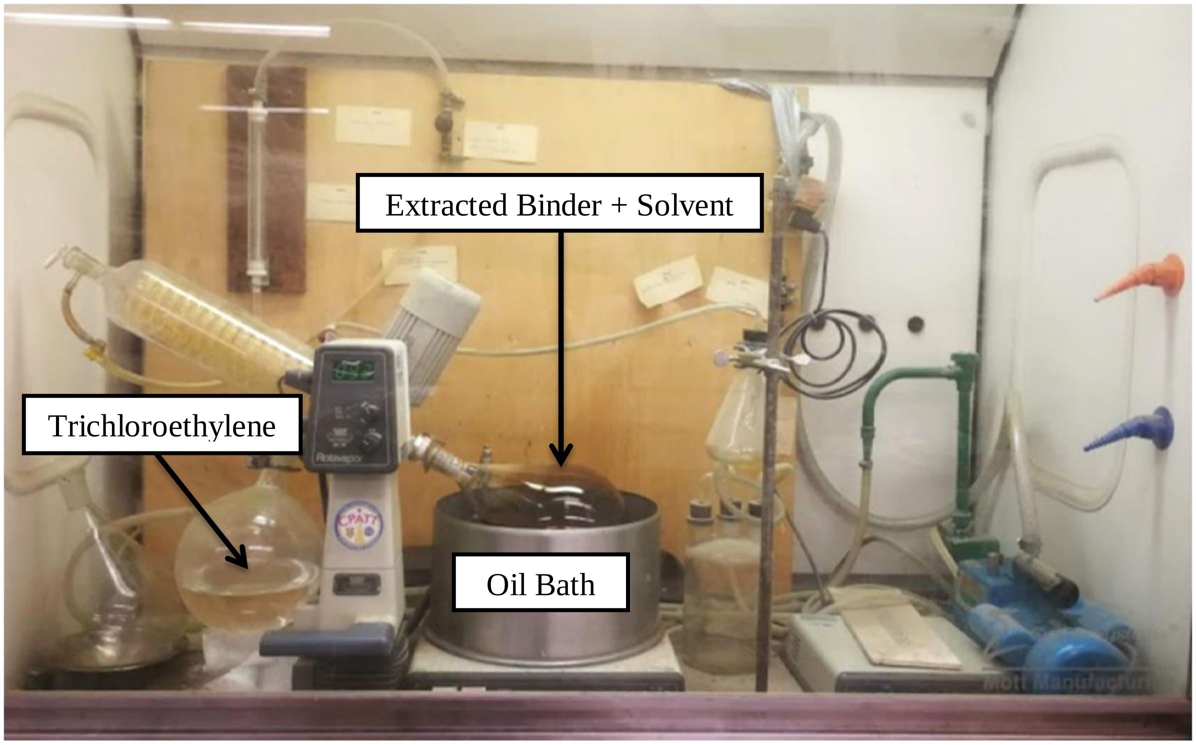


Figure 5.3: Rotary Evaporator In Use

5.5.2 Rolling Thin Film Oven (RTFO) Testing

RTFO testing was performed on RAP samples A, B, and C simultaneously in the CPATT lab following AASHTO T 240 specifications. The RTFO is a short term aging test, meant to simulate the aging which occurs on asphalt binder during the manufacturing and placement processes. With the 100% RAP mixtures, however, manufacturing will occur inside a portable infrared heating recycler, not the standard procedure the RTFO test is designed to simulate. It is still prudent to perform this test in order to follow the AASHTO M 320 procedure to properly grade the extracted binder. The RTFO test is performed by placing unaged asphalt binder in cylindrical glass bottles and inserting them into a carousel inside an oven. The oven is heated to a temperature of 163˚C, and the binder samples rotate around the carousel for 85 minutes. The samples are removed and stored for future testing once they are aged. Figure 5.4 below displays the RTFO testing machine used in the CPATT laboratory.

Figure 5.4: Left – CPATT's RTFO Interior, Right - RTFO Running

After sample A was tested, it was observed that the test bottle was not completely coated in asphalt binder, a requirement for the successful completion of a standard RTFO test. This error is common with highly viscous binders, such as polymer modified binders, or binders graded PG 70-XX and higher (Pavement Interactive 2019a). It can be concluded from this error that sample A binder is very viscous and stiff, possibly more aged then originally assumed.

5.5.3 Dynamic Shear Rheometer (DSR) Testing

DSR testing was performed on the RAP binder samples following AASHTO T 315 in order to determine the critical high temperatures for their performance gradings. This test was performed using a small amount of asphalt binder molded into a 1 mm thick, 25 mm diameter cylinder. This cylinder of binder was placed between two circular plates in the machine. The sample was then heated to the testing temperature and the two plates compress the binder and the top plate oscillates at 10 rad/sec. The machine records the maximum stress and strain experienced, and from this calculates the complex shear modulus (G*) and phase angle (δ), values which predict rutting and fatigue cracking potential of the binder respectively. Figure 5.5 below displays the DSR machine used, and binder sample B molded before testing.

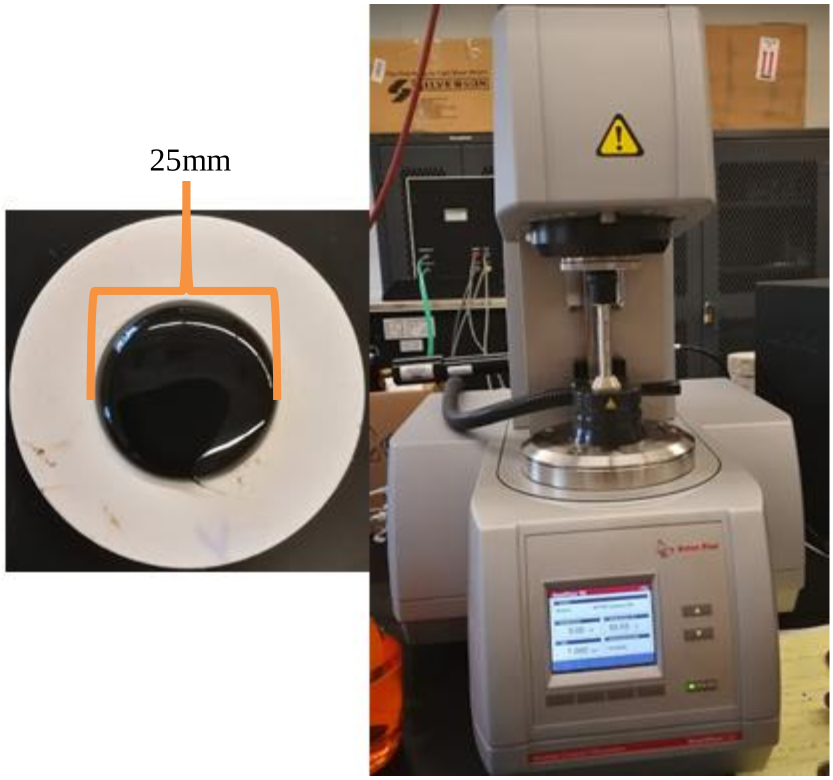


Figure 5.5: Left – DSR Binder "B" Sample, Right – CPATT's DSR Machine

In order to minimize rutting potential, the amount of work dissipated into pavement deformation by each traffic loading cycle needs to be minimized, this value is represented by complex shear modulus divided by the phase angle (G*/sin(δ)). DSR testing was performed on unaged extracted binder samples, and RTFO aged binder. The critical high temperatures for these tests are the highest temperatures at which G*/sin(δ) is greater than or equal to 1 kPa for unaged binder and 2.2 kPa for RTFO aged binder. The PG critical high temperatures obtained from DSR testing for each sample are summarized in Tables 5.4 and 5.5 below.

Table 5.4: Unaged Binder DSR Test Results (G*/sin(δ) ≥ 1.00 kPa)

Sample ID	Critical High Temperature (˚C)
A	118+
B	90.8
C	98.6

Table 5.5: RTFO Aged Binder DSR Test Results (G*/sin(δ) ≥ 2.20 kPa)

Sample ID	Critical High Temperature (˚C)
A	N/A
B	90
C	98.4

When tested, the unaged binder A passed at a critical high temperature of 118˚C, the highest temperature the DSR machine is able to reach. Therefore, the exact high temperature limitations of sample A could not be determined, but during the test sample A's G*/sin(δ) achieved a value of 5.05 kPa, well above the failure limit of 1 kPa, so it is predicted that the critical high temperature could be much higher. Sample A binder was unable to be properly molded into a testing cylinder following RTFO testing, so no aged DSR test was completed.

The critical high temperatures determined for the aged and unaged binders were very similar for samples B and C, with less than one degree differentiating them. This is expected considering the RAP samples were already aged from placement and years of service prior to testing.

5.5.4 Bending Beam Rheometer (BBR)

BBR testing was performed on the binder complying AASHTO standard T 313 after RTFO was completed on the samples to simulate the effects of short term aging. The BBR equipment measures the low temperature performance of the binder by calculating its stiffness. The test was performed first by pouring the asphalt binder into a constructed mold to form a beam measuring 6.25 mm x 12.5 mm x 127 mm. This beam was cooled at room temperature then trimmed to make the sample flush with the top of the mold. To remove the sample easily from the mold, it was first cooled at -5˚C for 5 minutes. Once removed, the beam was inserted into a cold fluid bath within the BBR set to the testing temperature for one hour. The binder beam was simply supported within the cold bath, and a load applied to the centre of the beam. The deflection of the beam is measured over time, and from this information the stiffness of the beam was calculated using standard beam theory. Figure 5.6 below displays the bending beam rheometer used, and illustrates the process of creating a beam for testing.

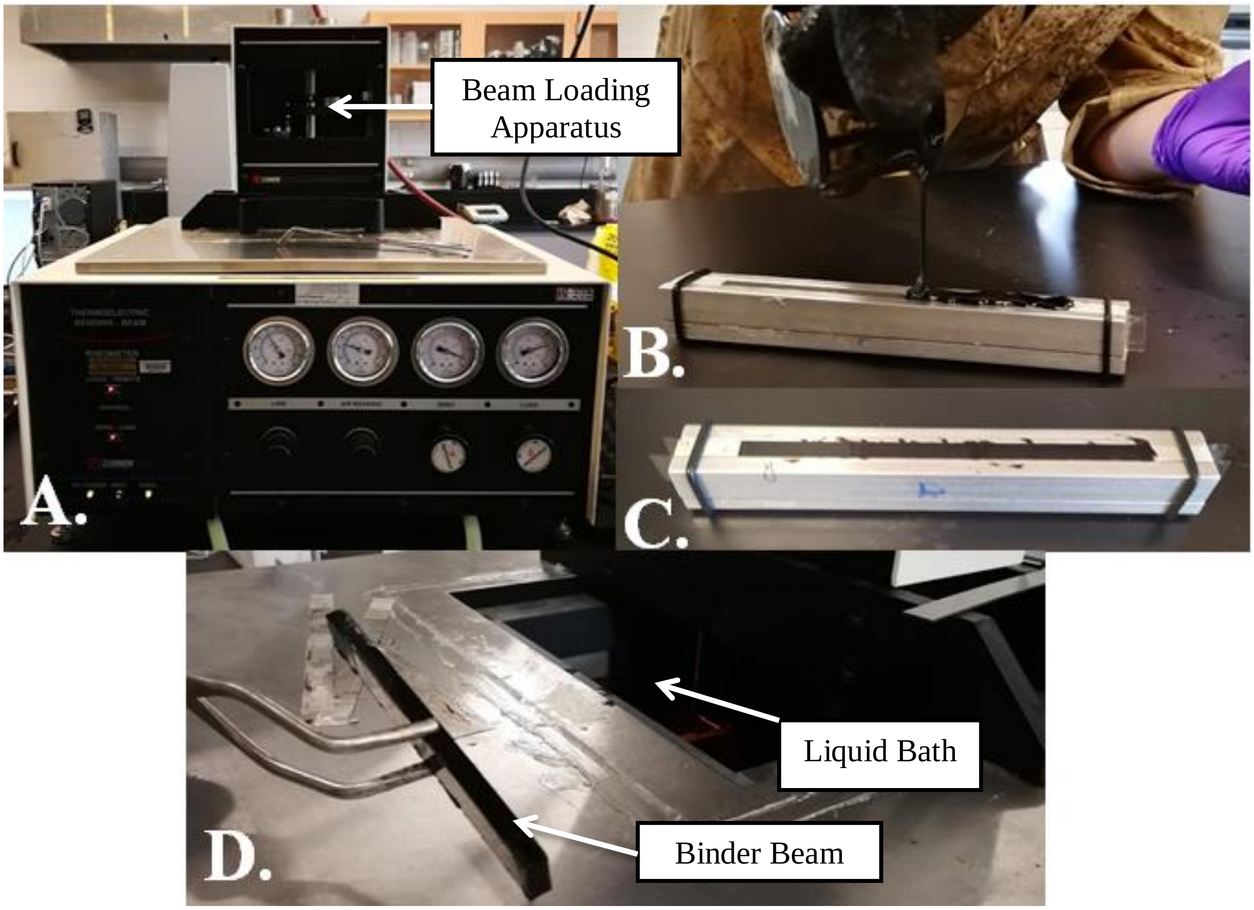


Figure 5.6: A – CPATT's BBR Machine, B – Sample B Being Poured into Mold, C – Sample B Trimmed, D – Sample B Beam Removed from Mold Entering Liquid Bath

Two BBR tests were completed on each binder sample, the first test at -12˚C, and the second at -18˚C. The calculated stiffness at the 60 second loading interval relative to the temperature of each test is displayed in Figure 5.7 below.

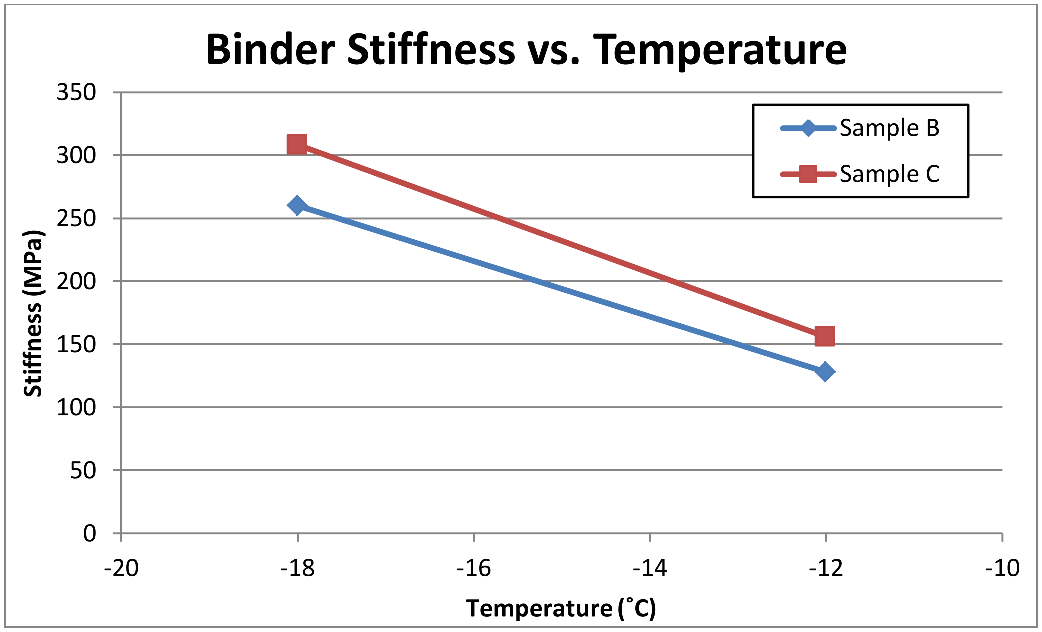


Figure 5.7: Binder Stiffness Graphed Against Tested Temperatures

The critical low temperature grading which the tested binder can perform correlates with the stiffness corresponding to an m-value of 0.3, minus 10˚C. The m-value is the slope of the master stiffness curve, which is the rate at which the asphalt binder relieves stress through plastic flow. Table 5.6 below displays the stiffness and critical low temperature calculated for each tested binder.

Table 5.6: BBR Test Results

Sample ID	Stiffness (MPa)	Critical Low Temperature (˚C)
A	N/A	N/A
B	191.3	-24.9
C	172.9	-22.7

The sample A BBR test could not be performed due to a lack of material retrieved from the RTFO container. The high stiffness and viscosity observed from the RTFO testing resulted in it being very difficult to retrieve binder from the testing cylinder, and not enough binder was recovered to fill the BBR mold. Figure 5.8 below displays the attempt at creating a BBR sample for RAP A.

Figure 5.8: RAP A BBR Sample

It is recommended to recover additional binder from RAP sample A and repeat all testing procedures in order to properly characterise this sample.

5.5.5 Performance Grading of RAP Samples

Based on the performed laboratory tests, the performance gradings for RAP samples A, B, and C were determined according to AASHTO M320, summarized in Table 5.7 below.

Table 5.7: PG of RAP Samples

Sample ID	PG (˚C)
A	118 -XX
B	90 -24.9
C	98.4 -22.7

The critical high temperatures from the RTFO aged binders were used in the PG because they tested slightly lower than the unaged binders. The PG critical temperatures achieved from testing appear representative of a typical aged binder (Alavi, He, and Jones 2014).

5.5.6 Gradation Testing

Gradation testing was performed on RAP aggregates collected from the extraction testing following ASTM standard D 6913. Figure 5.9 below displays the gradation charts created for RAP samples A, B, and C compared to the OPSS gradation standards for HMA surface courses.

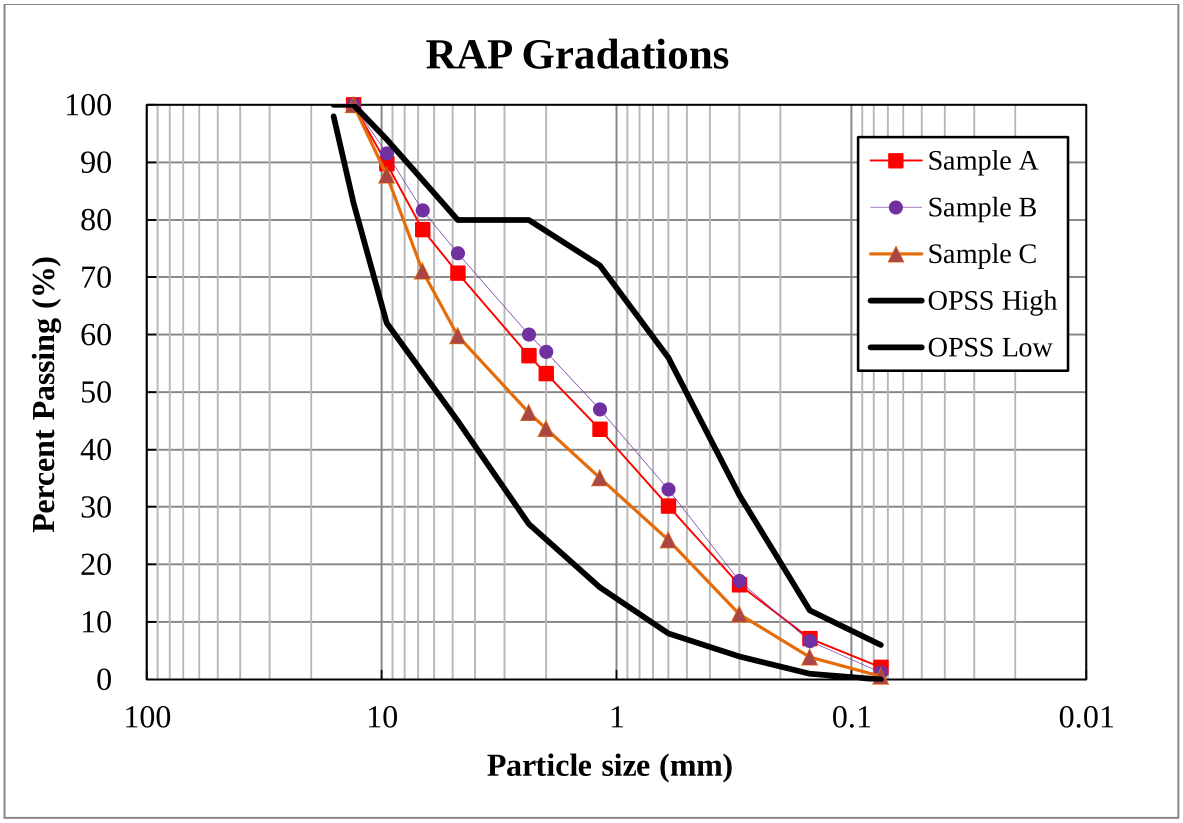


Figure 5.9: Particle Distribution Graph for RAP Samples A, B, and C

The gradations of the three different RAP sources are all very similar. This is to be expected because all sources started from surface course HMA mixtures which are all specified to similar gradations requirements. Samples B and C were also processed through the same crushing machine at the same particle size setting. The percent gravel, sand, and fines calculated for each RAP sample are summarized on Table 5.8 below.

Table 5.8: Gradation Test Results

Sample ID	% Gravel	% Sand	% Fines
A	29.33	68.58	2.09
B	25.86	73.01	1.13
C	40.18	59.34	0.48

All three RAP samples comply with Ontario provincial standards for gradation of surface course HMA mixtures (OPSS 2013). Gradations containing a large amount of fine material cause the asphalt to distort and cause rutting quicker, similarly to that of a mixture with too much asphalt binder content. These low fines percentages work together well with the high binder contents recorded.

5.6 Summary of Testing

Table 5.9 below summarises the results of laboratory tests performed on the RAP samples which will be used in creating 100% RAP patching mixtures.

Table 5.9: Summary of RAP Testing

Test Criteria	RAP - A	RAP - B	RAP - C
Binder Content (%)	5.97	6.05	5.40
Critical High Temperature (˚C)	118+	90.0	98.4
Critical Low Temperature (˚C)	N/A	-24.9	-22.7
Gradation Results			
% Gravel	29.33	25.86	40.18
% Sand	68.58	73.01	59.34
% Fines	2.09	1.13	0.48

Out of all RAP samples tested, sample A (RAP bricks) was predicted to perform the best, but ended up performing very poorly, often unable to properly complete testing procedures because of its highly viscous state. It is predicted that somewhere in the mixing, collection, and stockpiling process, this material was subjected to stimuli which accelerated the ageing of the material. The properties tested and observed from working with this material should be confirmed by further testing after extracting more binder material from the RAP sample. RAP samples B and C both produced promising high binder contents for recycled materials, and throughout the binder characterization process performed well achieving performance gradings of 90 -24.9, and 98.4 -22.7 respectively.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This research has explored the use of infrared heating technology in multiple asphalt pavement repair methods and construction scenarios. It is intended to advance knowledge surrounding this relatively new pavement repair technique and validate its performance in order for future projects to consider using this maintenance strategy, and to provide information for future provincial standards to include infrared heating. Increased use of infrared heating repairs will utilize more in-place and recycled RAP materials, moving the paving industry in a more sustainable, environmentally friendly, and economically viable direction.

When comparing infrared heating repairs to more conventionally used crack and pothole repair methods such as crack sealing, crack filling, and mill and replacement, the following specific conclusions were drawn:

1. The thermal bond provided by infrared heating is proven to create a stronger, longer lasting seal between the repaired surface and the in place asphalt then the cold joints used in the other researched methods. This thermally bonded joint is innately part of the infrared heating patch and joint repair process, but can be utilized with joint construction and mill and replace operations to provide a superior repair.
2. When compared to other commonly used repair methods, infrared heating can provide more versatile repairs. Crack sealing and crack filling are only viable for small to moderate sized repairs, and mill and replace is generally used for only large scale repairs. Infrared heating is more flexible in its application as it can accommodate repair areas of all sizes, which is useful when one site requires simultaneous repair of different magnitudes.
3. Crack sealing and crack filling provide the quickest repair time, and are ideal for projects with large user costs associated with traffic interference. Infrared heating does require slightly longer individual repair times, however, the repairs last longer resulting in a reduction of the overall maintenance time over the pavement's service life.

4. Infrared heating repairs require specialized machinery and expertise to properly implement, as such, these services are not currently available widespread, resulting in increased transportation costs associated with projects located far from where these services can be provided.
5. Crack sealing and crack filling provide the least expensive repair options, followed by infrared heating, and mill and replacement as the most expensive, but longest lasting repair option. The budget available in the calendar year plays a significant factor in the type of repair process able to be administered.
6. Infrared heating repairs were observed to last upwards of ten years in situations where other infrastructure wasn't inflicting additional stresses on the pavement surface.

In Chapter 4, the progress of an ongoing infrared heating repair pilot project between the City of Waterloo, HDE, and CPATT was discussed. The condition of Sugarbush Drive was visually inspected, then borehole, granular base, and subgrade samples were extracted and tested in the CPATT laboratory to determine the properties of the in-place materials. The average asphalt binder content of the 75 mm thick surface course was calculated to be 7.21%. Gradation and proctor testing was performed on the granular base and subgrade materials, which found these layers to be performing adequately. LWD testing was performed on Sugarbush Drive, concluding average surface deflection moduli of 280 MPa. With the test results, an accurate understanding of the structure and composition of Sugarbush Drive was achieved, and recommendations were made for a suitable repair plan.

Chapter 5 introduced a project planning to create a patching mixture to be used in infrared heating or crack filling style repairs, containing 100% recycled pavement materials as a base, created in a portable infrared heating recycler, adding only rejuvenators to increase the flexibility and malleability of the mix. Multiple laboratory tests were completed on three RAP samples intended to be the major component of the patching mixtures in order to determine their current properties as a baseline, and characterize their binder properties. Tests performed included asphalt binder extractions, aggregate gradation testing, RTFO, DSR, and BBR. RAP sample A consisted of unused virgin asphalt concrete materials delivered by a local manufacturer, sample B contained aged ripoff from local municipalities' excess materials, and sample C was scrapings and milled RAP materials. RAP sample A was predicted to perform the best considering it had never been used in service before, and RAP C was predicted to perform the worst since it consisted of the oldest materials. These predictions, however, were proven false after RAP A's binder was found to be a very viscous and stiff material, often unable to properly conform to standard testing procedures. Samples B and C performed well, exhibiting high AC contents of 6.05% and 5.40% respectively, while achieving PG's of 90 -24.9, and 98.4 -22.7, considered standard for RAP materials.

6.2 Recommendations for Future Work

Based on the research completed, the following areas are recommended for future work:

- Infrared Heating Repair Research:

1. The long term ageing process of infrared heating style repairs should continue to be studied, including repair monitoring from creation to a state where additional repairs are required. This includes continual studies on Sugarbush Drive.

- Sugarbush Drive Rehabilitation:

1. It is recommended to proceed with the tier 2 option proposed for the rehabilitation of Sugarbush Drive, involving full lane width infrared heating rehabilitation on the entire street. This option will provide a completely repaired, seamless pavement structure with an improved roadway profile to assist drainage.
2. Based on the performance of major roadway rehabilitation with infrared heating, the City of Waterloo can observe the performance first hand and determine if they want to add this type of repair into their constant rotation.

- 100% RAP Patching Mixture

1. It is recommended to complete additional binder testing on RAP sample A to confirm the unique properties observed, and run BBR tests and RTFO aged DSR tests, since not enough binder was extracted to complete the tests this round.

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Appendix A - Sugarbush Drive Laboratory Data

LOG OF BOREHOLE BH19-1

wood.

JOB NUMBER: SCC197104-11	**DRILLING DATA**
CLIENT: CoW / UoW	DESCRIPTION: ☑ Track Mount ☐ Truck Mount ☐ ______
PROJECT NAME: Sugarbush and Whitmore	METHOD: ☑ Hollow Stem ☐ Solid Stem ☐ ______
LOCATION: E0539161, N4816644	DIAMETER: ☐ 150 mm (6 in) ☑ 200 mm (8 in) ☐ ______
DATUM: NAD83 SURFACE: Asphalt	START TIME: 10:45 FINISH TIME:
DRILLING CONTRACTOR: GF	SUPERVISOR: JW
DRILL RIG TYPE: Geoprobe	TOTAL DEPTH DRILLED:
DRILLER: Dylan / Justin	Date: May 30, 2019

FIELD DATA				Depth Below Surf. (m)	SAMPLES					Depth Below Surf. (ft)	MATERIAL DESCRIPTION	Well Constr. & Materials	REMARKS
Vane Test		Pocket	Total										
Field Peak (lb.ft)	Field Rem. (lb.ft)	Pen Test (tsf)	Organic Vapour (ppm)		Sample Type	Sample Number	Recovery	Blows Per 0.15m/6"	N-Value or DCPT		Notes: colour, soil description, structure, density, consistency, plasticity, and moisture conditions		Notes: weather, snow cover, frost depth, caving, refusal, coring, well details, and times for breakdowns, relocation, crew changes
				0.30						1.0	60 mm of Asphalt		8" Asphalt Coring
				0.61						2.0	(280mm-60mm) of Granular Fill, moist		
				0.91						3.0	(500mm-250mm) of subgrade, Dark Brown to Black Silty Sand		
				1.22						4.0	Fill, trace gravel, trace clay, trace organics moist		
				1.52						5.0			
				1.83						6.0			
				2.13						7.0			
				2.44						8.0			
				2.74						9.0			
				3.05						10.0			
				3.35						11.0			
				3.66						12.0			
				3.96						13.0			
				4.27						14.0			
				4.57						15.0			
				4.88						16.0			
				5.18						17.0			
				5.49						18.0			
				5.79						19.0			
				6.10						20.0			

Date & Time: __________ @ ______ am / pm Water Level: __________ Cave In: __________ Logged By: __________

Date & Time: __________ @ ______ am / pm Water Level: __________ Cave In: __________ Sheet 1 of : __________

C:\Users\joe.wang2\Documents\2018\Template\Borehole\[Borehole Log.xls]Sheet2

LOG OF BOREHOLE BH19-2

wood.

JOB NUMBER: SCC197104.11		**DRILLING DATA**	
CLIENT: CoW / VoW		DESCRIPTION: ☑ Track Mount ☐ Truck Mount ☐ ______	
PROJECT NAME: Sugarbush and Whitmore		METHOD: ☐ Hollow Stem ☐ Solid Stem ☐ ______	
LOCATION: E0539133, N4816684		DIAMETER: ☐ 150 mm (6 in) ☐ 200 mm (8 in) ☐ ______	
DATUM: NAD83	SURFACE: Asphalt	START TIME: 10:20	FINISH TIME:
DRILLING CONTRACTOR: OF		SUPERVISOR: JW	
DRILL RIG TYPE: Geoprobe		TOTAL DEPTH DRILLED:	
DRILLER: Dylan / Justin		Date: May 30, 2019	

FIELD DATA				Depth Below Surf. (m)	SAMPLES					Depth Below Surf. (ft)	MATERIAL DESCRIPTION	Well Constr. & Materials	REMARKS
Vane Test		Pocket Pen Test (tsf)	Total Organic Vapour (ppm)		Sample Type	Sample Number	Recovery	Blows Per 0.15m/6"	N-Value or DCPT		Notes: colour, soil description, structure, density, consistency, plasticity, and moisture conditions		Notes: weather, snow cover, frost depth, caving, refusal, coring, well details, and times for breakdowns, relocation, crew changes
Field Peak (lb.ft)	Field Rem. (lb.ft)												
				0.30						1.0	75 mm of Asphalt		8" Asphalt Coring
				0.61						2.0			
				0.91						3.0			
				1.22						4.0			
				1.52						5.0			
				1.83						6.0			
				2.13						7.0			
				2.44						8.0			
				2.74						9.0			
				3.05						10.0			
				3.35						11.0			
				3.66						12.0			
				3.96						13.0			
				4.27						14.0			
				4.57						15.0			
				4.88						16.0			
				5.18						17.0			
				5.49						18.0			
				5.79						19.0			
				6.10						20.0			

Date & Time: __________ @ ______ am / pm Water Level: __________ Cave In: __________ Logged By: __________

Date & Time: __________ @ ______ am / pm Water Level: __________ Cave In: __________ Sheet 1 of : __________

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LOG OF BOREHOLE BH19-3

wood.

JOB NUMBER: SCC197164.11	**DRILLING DATA**
CLIENT: CoW / UoW	DESCRIPTION: ☑ Track Mount ☐ Truck Mount ☐ ______
PROJECT NAME: Sugarbush and Whitmore	METHOD: ☑ Hollow Stem ☐ Solid Stem ☐ ______
LOCATION: E0539139 N4816729	DIAMETER: ☐ 150 mm (6 in) ☑ 200 mm (8 in) ☐ ______
DATUM: NAD83 SURFACE: Asphalt	START TIME: 10:00 FINISH TIME:
DRILLING CONTRACTOR: GF	SUPERVISOR: JW
DRILL RIG TYPE: Geoprobe	TOTAL DEPTH DRILLED: 2'
DRILLER: Dylan / Justin	Date: May 30, 2019

FIELD DATA: Vane Test Field Peak (lb.ft)	Vane Test Field Rem. (lb.ft)	Pocket Pen Test (tsf)	Total Organic Vapour (ppm)	Depth Below Surf (m)	SAMPLES: Sample Type	Sample Number	Recovery	Blows Per 0.15m/6"	N-Value or DCPT	Depth Below Surf. (ft)	MATERIAL DESCRIPTION (Notes: colour, soil description, structure, density, consistency, plasticity, and moisture conditions)	Well Constr. & Materials	REMARKS (Notes: weather, snow cover, frost depth, caving, refusal, coring, well details, and times for breakdowns, relocation, crew changes)
				0.30						1.0	75 mm of Asphalt		8" Asphalt Coring
				0.61						2.0	(320mm-75mm) of Granular Base/subbase, moist		
				0.91						3.0			
				1.22						4.0	(2'-320mm) of Subgrade, Brown silty Sand, some gravel, trace organics, trace clay, moist		
				1.52						5.0			
				1.83						6.0			
				2.13						7.0			
				2.44						8.0			
				2.74						9.0			
				3.05						10.0			
				3.35						11.0			
				3.66						12.0			
				3.96						13.0			
				4.27						14.0			
				4.57						15.0			
				4.88						16.0			
				5.18						17.0			
				5.49						18.0			
				5.79						19.0			
				6.10						20.0			

Date & Time: ______ @ ______ am / pm Water Level: ______ Cave In: ______ Logged By: ______

Date & Time: ______ @ ______ am / pm Water Level: ______ Cave In: ______ Sheet **1** of : ______

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LOG OF BOREHOLE BH19-4

wood.

JOB NUMBER: SCC197104.11	**DRILLING DATA**
CLIENT: CoW / VoW	DESCRIPTION: ☑ Track Mount ☐ Truck Mount ☐
PROJECT NAME: Sugarbush and Whitmore	METHOD: ☑ Hollow Stem ☐ Solid Stem ☐
LOCATION: E0539171 N4816828	DIAMETER: ☐ 150 mm (6 in) ☑ 200 mm (8 in) ☐
DATUM: NAD83 SURFACE: Asphalt	START TIME: 9:00 AM FINISH TIME:
DRILLING CONTRACTOR: GF	SUPERVISOR: JW
DRILL RIG TYPE: Geoprobe	TOTAL DEPTH DRILLED: ~4'
DRILLER: Dylan / Justin	Date: May 30, 2019

FIELD DATA: Vane Test Field Peak (lb.ft)	Vane Test Field Rem. (lb.ft)	Pocket Pen Test (tsf)	Total Organic Vapour (ppm)	Depth Below Surf. (m)	SAMPLES: Sample Type	Sample Number	Recovery	Blows Per 0.15m/6"	N-Value or DCPT	Depth Below Surf. (ft)	MATERIAL DESCRIPTION: Notes: colour, soil description, structure, density, consistency, plasticity, and moisture conditions	Well Constr. & Materials	REMARKS: Notes: weather, snow cover, frost depth, caving, refusal, coring, well details, and times for breakdowns, relocation, crew changes
											90 mm of Asphalt		8" Asphalt Coring
				0.30						1.0			
											2' of Granular Base / Subbase, moist. trace cobble		Switched to 8" Auger
				0.61						2.0			
				0.91						3.0	2' of Subgrade, Brown silty Sand, trace to some gravel, trace organics, trace clay, moist		
				1.22						4.0			
				1.52						5.0			
				1.83						6.0			
				2.13						7.0			
				2.44						8.0			
				2.74						9.0			
				3.05						10.0			
				3.35						11.0			
				3.66						12.0			
				3.96						13.0			
				4.27						14.0			
				4.57						15.0			
				4.88						16.0			
				5.18						17.0			
				5.49						18.0			
				5.79						19.0			
				6.10						20.0			

Date & Time: ________ @ ______ am / pm Water Level: ________ Cave In: ________ Logged By: ________

Date & Time: ________ @ ______ am / pm Water Level: ________ Cave In: ________ Sheet 1 of : ________

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LOG OF BOREHOLE BH19-5

wood.

JOB NUMBER: SCC197104.11	**DRILLING DATA**
CLIENT: CoW / UoW	DESCRIPTION: ☑ Track Mount ☐ Truck Mount ☐
PROJECT NAME: Sugarbush and Whitmore	METHOD: ☑ Hollow Stem ☐ Solid Stem ☐
LOCATION: E0539870 N4816466	DIAMETER: ☐ 150 mm (6 in) ☑ 200 mm (8 in) ☐
DATUM: NAD83 SURFACE: Asphalt	START TIME: FINISH TIME:
DRILLING CONTRACTOR: GF	SUPERVISOR: JW
DRILL RIG TYPE: Geoprobe	TOTAL DEPTH DRILLED:
DRILLER: Dylan / Justin	Date: May 30, 2019

FIELD DATA: Vane Test Field Peak (lb.ft)	Vane Test Field Rem. (lb.ft)	Pocket Pen Test (tsf)	Total Organic Vapour (ppm)	Depth Below Surf. (m)	SAMPLES: Sample Type	Sample Number	Recovery	Blows Per 0.15 m/6"	N-Value or DCPT	Depth Below Surf. (ft)	MATERIAL DESCRIPTION (Notes: colour, soil description, structure, density, consistency, plasticity, and moisture conditions)	Well Constr. & Materials	REMARKS (Notes: weather, snow cover, frost depth, caving, refusal, coring, well details, and times for breakdowns, relocation, crew changes)
				0.30						1.0	60 mm of Asphalt		8" Asphalt Coring
				0.61						2.0	(60mm - 400mm) of Granular Fill moist		
				0.91						3.0	(400mm - 600mm) of Subgrade, Brown Silty Sand Fill, Some gravel, trace Organics, moist		
				1.22						4.0			
				1.52						5.0			
				1.83						6.0			
				2.13						7.0			
				2.44						8.0			
				2.74						9.0			
				3.05						10.0			
				3.35						11.0			
				3.66						12.0			
				3.96						13.0			
				4.27						14.0			
				4.57						15.0			
				4.88						16.0			
				5.18						17.0			
				5.49						18.0			
				5.79						19.0			
				6.10						20.0			

Date & Time: ________ @ ______ am / pm Water Level: ________ Cave In: ________ Logged By: ________

Date & Time: ________ @ ______ am / pm Water Level: ________ Cave In: ________ Sheet 1 of : ________

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LOG OF BOREHOLE BH19-6

wood.

JOB NUMBER: SCC197104.11	**DRILLING DATA**
CLIENT: CoW / UoW	DESCRIPTION: ☑ Track Mount ☐ Truck Mount ☐ ______
PROJECT NAME: Sugarbush and Whitmore	METHOD: ☑ Hollow Stem ☐ Solid Stem ☐ ______
LOCATION: E0539866, N4816287	DIAMETER: ☐ 150 mm (6 in) ☑ 200 mm (8 in) ☐ ______
DATUM: NAD83 SURFACE: Asphalt	START TIME: 11:50 FINISH TIME:
DRILLING CONTRACTOR: GF	SUPERVISOR: JW
DRILL RIG TYPE: Geoprobe	TOTAL DEPTH DRILLED:
DRILLER: Dylan / Justin	Date: May 30, 2019

FIELD DATA				Depth	SAMPLES					Depth	MATERIAL DESCRIPTION		REMARKS
Vane Test		Pocket	Total	Below						Below			
Field Peak (lb/ft)	Field Rem. (lb/ft)	Pen Test (tsf)	Organic Vapour (ppm)	Surf. (m)	Sample Type	Sample Number	Recovery	Blows Per 0.15m/6"	N-Value or DCPT	Surf. (ft)	Notes: colour, soil description, structure, density, consistency, plasticity, and moisture conditions	Well Constr. & Materials	Notes: weather, snow cover, frost depth, caving, refusal, coring, well details, and times for breakdowns, relocation, crew changes
				0.30						1.0	75 mm of Asphalt		8" Asphalt Coring
				0.61						2.0	(330mm-75mm) of Granular Fill, moist		
				0.91						3.0	(700mm-330mm) of Subgrade		
				1.22						4.0	Brown Silty Sand Fill, trace to some gravel, trace clay, moist		
				1.52						5.0			
				1.83						6.0			
				2.13						7.0			
				2.44						8.0			
				2.74						9.0			
				3.05						10.0			
				3.35						11.0			
				3.66						12.0			
				3.96						13.0			
				4.27						14.0			
				4.57						15.0			
				4.88						16.0			
				5.18						17.0			
				5.49						18.0			
				5.79						19.0			
				6.10						20.0			

Date & Time: ____________ @ ______ am / pm Water Level: ____________ Cave In: ____________ Logged By: ____________

Date & Time: ____________ @ ______ am / pm Water Level: ____________ Cave In: ____________ Sheet 1 of : ____________

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Asphalt Binder Extraction Data Sugarbush Drive

Sample	BH 19-1		BH 19-2		BH 19-3		BH 19-4	
Initial Weight (g)	1077.6	1093.5	1159.1	1153.9	1031.9	1079.1	1257.4	1118
Final Weight	994.8	1009.4	1073.3	1076.5	962.1	1010.7	1166.4	1030.5
%AC	7.68	7.69	7.40	6.71	6.76	6.34	7.24	7.83
Average %AC	7.69		7.05		6.55		7.53	
Road Average %AC	7.21							

Asphalt Binder Extraction Data Whitmore Drive

Sample	BH 19-5		BH 19-6	
Initial Weight (g)	1377.6	1077.6	1058	1092.8
Final Weight	1266.1	972.7	988.2	1022.5
%AC	8.09	9.73	6.6	6.43
Average %AC	8.91		6.51	
Road Average %AC	7.71			

Gradation Tables for Sugarbush Drive Granular Materials

Granular BH19-1				
Sieve (mm)	**Weight (g)**	**Cumulative (g)**	**% retained**	**%passing (%)**
63	0	0	0.0%	100.00%
37.5	393.3	180.8	4.0%	96.00%
26.5	435	615.8	8.4%	91.60%
19	424.6	1040.4	12.7%	87.30%
16	302.7	1343.1	15.8%	84.20%
13.2	528.8	1871.9	21.2%	78.80%
9.5	963.9	2835.8	30.9%	69.10%
6.7	798	3633.8	39.0%	61.00%
4.75	553.7	4187.5	44.7%	55.30%
2.36	33	33	51.8%	48.20%
1.18	26	59	57.4%	42.60%
0.6	30.5	89.5	64.0%	36.00%
0.3	36.7	126.2	71.9%	28.10%
0.15	25.8	152	77.4%	22.60%
0.075	24.7	176.7	82.8%	17.20%
Pan	5232	5408.7	55.14%	0.00%
Sum	9808.7			
Initial Total Weight	9851.1			

Granular BH19-3				
Sieve (mm)	Weight (g)	Cumulative (g)	% retained	%passing (%)
63	0	0	0.0%	100.0%
37.5	0	0	0.0%	100.0%
26.5	227.5	227.5	2.2%	97.8%
19	643.4	870.9	8.6%	91.4%
16	483.9	1354.8	13.4%	86.6%
13.2	677	2031.8	20.1%	79.9%
9.5	1027	3058.8	30.2%	69.8%
6.7	817.9	3876.7	38.3%	61.7%
4.75	627.4	4504.1	44.5%	55.5%
2.36	48.5	48.5	54.7%	45.3%
1.18	27.5	76	60.5%	39.5%
0.6	24.9	100.9	65.7%	34.3%
0.3	29.5	130.4	71.9%	28.1%
0.15	23.5	153.9	76.8%	23.2%
0.075	25.9	179.8	82.3%	17.7%
Pan	5430.4	5610.2	57.20%	0.00
	10114.3			
Initial Total Weight	10127.7			

Granular BH19-4				
Sieve (mm)	Weight (g)	Cumulative (g)	% retained	%passing (%)
63	0	0	0.0%	100.0%
37.5	759.5	180.8	8.0%	92.0%
26.5	65.3	246.1	8.8%	91.2%
19	463.4	709.5	13.7%	86.3%
16	220.5	930	16.0%	84.0%
13.2	555.7	1485.7	21.9%	78.1%
9.5	686.1	2171.8	29.2%	70.8%
6.7	1171	3342.8	41.7%	58.3%
4.75	602.6	3945.4	48.1%	51.9%
2.36	50.3	50.3	58.5%	41.5%
1.18	39.3	89.6	66.7%	33.3%
0.6	33.3	122.9	73.6%	26.4%
0.3	36	158.9	81.0%	19.0%
0.15	21.8	180.7	85.6%	14.4%
0.075	17.7	198.4	89.2%	10.8%

Pan	2582.9	2781.3	28.36%	0.00
	7305.4			
Initial Total Weight	9406.1			

Granular BH19-5				
Sieve (mm)	**Weight (g)**	**Cumulative (g)**	**% retained**	**%passing (%)**
63	0	0	0.0%	100.0%
37.5	180.8	180.8	2.0%	98.0%
26.5	403.3	584.1	6.6%	93.4%
19	1531.2	2115.3	23.8%	76.2%
16	633.5	2748.8	30.9%	69.1%
13.2	662.3	3411.1	38.4%	61.6%
9.5	1121	4532.1	51.0%	49.0%
6.7	739.4	5271.5	59.4%	40.6%
4.75	427.6	5699.1	64.2%	35.8%
2.36	46.9	46.9	70.7%	29.3%
1.18	29.7	76.6	74.7%	25.3%
0.6	38.5	115.1	80.0%	20.0%
0.3	37	152.1	85.1%	14.9%
0.15	23.5	175.6	88.4%	11.6%
0.075	20.4	196	91.2%	8.8%
Pan	2976.4	3172.4	32.34%	0.00
	8871.5			
Initial Total Weight	8881.7			

Gradation Tables for Sugarbush Drive Subgrade Materials

Subgrade BH19-1				
Sieve (mm)	**Weight (g)**	**Cumulative (g)**	**% retained**	**%passing (%)**
63	0	0	0.0%	100.0%
37.5	120.7	120.7	2.4%	97.6%
26.5	0	120.7	2.4%	97.6%
19	0	120.7	2.4%	97.6%
16	86.2	206.9	4.1%	95.9%
13.2	56.7	263.6	5.2%	94.8%
9.5	147.7	411.3	8.1%	91.9%
6.7	131.3	542.6	10.7%	89.3%
4.75	134.7	677.3	13.4%	86.6%

2.36	13.4	13.4	17.6%	82%
1.18	13.4	26.8	21.9%	78.1%
0.6	19.3	46.1	28.0%	72.0%
0.3	24.3	70.4	35.8%	64.2%
0.15	25.2	95.6	43.8%	56.2%
0.075	33	128.6	54.3%	45.7%
Pan	4245.5	4374.1	44.59%	55.41
	5051.4			
Initial Total Weight	5051.4			

Subgrade BH19-3				
Sieve (mm)	**Weight (g)**	**Cumulative (g)**	**% retained**	**%passing (%)**
63	0	0	0.0%	100.0%
37.5	0	0	0.0%	100.00%
26.5	46.1	46.1	1.0%	99.00%
19	97.1	143.2	2.5%	97.50%
16	49	192.2	3.4%	96.60%
13.2	87.9	280.1	5.0%	95.00%
9.5	171.5	451.6	8.0%	92.00%
6.7	146.1	597.7	10.6%	89.40%
4.75	151.7	749.4	13.3%	86.70%
2.36	14.3	14.3	18.0%	82.00%
1.18	14.5	28.8	22.8%	77.20%
0.6	31.2	60	33.2%	66.80%
0.3	22.6	82.6	40.7%	59.30%
0.15	32	114.6	51.3%	48.70%
0.075	41.8	156.4	71.1%	28.90%
Pan	4538.8	4695.2	47.87%	52.13
	5444.6			
Initial Total Weight	5633.2			

Subgrade BH19-4				
Sieve (mm)	**Weight (g)**	**Cumulative (g)**	**% retained**	**%passing (%)**
63	0	0	0.0%	100.0%
37.5	0	0	0.0%	100.00%
26.5	51	51	1.0%	99.00%
19	95.4	146.4	2.8%	97.20%
16	63.6	210	4.1%	95.90%

13.2	116.2	326.2	6.3%	93.70%
9.5	233.5	559.7	10.9%	89.10%
6.7	176.8	736.5	14.3%	85.70%
4.75	152.3	888.8	17.3%	82.70%
2.36	14.2	14.2	21.7%	78.30%
1.18	13	27.2	25.7%	74.30%
0.6	17.9	45.1	31.3%	68.70%
0.3	26.6	71.7	39.5%	60.50%
0.15	25	96.7	47.3%	52.70%
0.075	42.4	139.1	60.3%	39.70%
Pan	4100.8	4239.9	43.23%	56.77
	5128.7			
Initial Total Weight	5137.2			

Subgrade BH19-5				
Sieve (mm)	**Weight (g)**	**Cumulative (g)**	**% retained**	**%passing (%)**
63	0	0	0.0%	100.0%
37.5	0	0	4.0%	96.00%
26.5	27.4	27.4	8.4%	91.60%
19	47.6	75	12.7%	87.30%
16	43.6	118.6	15.8%	84.20%
13.2	70.3	188.9	21.2%	78.80%
9.5	190.8	379.7	30.9%	69.10%
6.7	183.4	563.1	39.0%	61.00%
4.75	138.8	701.9	44.7%	55.30%
2.36	14.1	14.1	51.8%	48.20%
1.18	12.5	26.6	57.4%	42.60%
0.6	24.3	50.9	64.0%	36.00%
0.3	25.5	76.4	71.9%	28.10%
0.15	19.2	95.6	77.4%	22.60%
0.075	20.3	115.9	82.8%	17.20%
Pan	4499.4	4615.3	47.05%	52.95
	5317.2			
Initial Total Weight	5445.2			

Granular Base Proctor Test Data

Granular BH19-5				
	in^3	cm^3	m^3	
volume of mold	170.8361	2799.502	0.002799502	
sample mass (g)	8003.2			
Test no	1	2	3	4
water added (%)	0.02	0.04	0.06	0.08
mold + wet soil	12558.2	12801.9	13301.1	13349.1
tare	6530	6530	6530	6530
wet soil mass (g)	6028.2	6271.9	6771.1	6819.1
wet soil mass (KN)	0.059117	0.061507	0.066402146	0.066873
wet density (g/cm^3)	2.153312	2.240363	2.418680493	2.435826
Unit Weight (KN/m^3)	21.11688	21.97057	23.71927399	23.88742
tin + wet soil	87	110.9	145.8	129.7
tin + dry soil	84.5	104.7	135.6	117.6
moisture loss	2.5	6.2	10.2	12.1
tare	4.1	4.1	4	4.1
dry soil mass	80.4	100.6	131.6	113.5
% moist	2.99	6.16	7.75	10.66
dry density	2.090797	2.110365	2.244715075	2.201181

Granular BH19-3				
	in^3	cm^3	m^3	
volume of mold	170.8361	2799.502	0.002799502	
sample mass (g)	8519.3			
Test no	1	2	3	4
water added (%)	0.04	0.06	0.08	0.1
mold + wet soil	12919.4	13261.6	13237.4	13119.3
tare	6530	6530	6530	6530
wet soil mass (g)	6389.4	6731.6	6707.4	6589.3
wet soil mass (KN)	0.062659	0.066015	0.06577746	0.064619
wet density (g/cm^3)	2.282335	2.404571	2.395926443	2.35374
Unit Weight (KN/m^3)	22.38217	23.5809	23.49613185	23.08243
tin + wet soil	75.3	98.9	137.2	171.7
tin + dry soil	72.1	92.5	126.2	156.6
moisture loss	3.2	6.4	11	15.1
tare	4.1	4.1	4.1	4.1
dry soil mass	68	88.4	122.1	152.5
% moist	4.71	7.24	9.01	9.9
dry density	2.179672	2.242233	2.197896012	2.141711

Subgrade Proctor Test Data

Subgrade BH19-5					
			m^3	mm^3	
volume of mold			9.9317E+13	99317	
sample mass (g)	5011.6				
Test no	1	2	3	4	5
water added (%)	0.04	0.06	0.08	0.1	0.12
mold + wet soil	7021.3	7146.5	7231.2	7237	7207.2
tare	5125.7	5125.7	5125.7	5125.7	5125.7
wet soil mass (g)	1895.6	2020.8	2105.5	2111.3	2081.5
wet soil mass (KN)	0.01859	0.019817	0.020648007	0.020705	0.020413
wet density (g/cm^3)	0.677121	0.721843	0.752098149	0.75417	0.743525
Unit Weight (KN/m^3)	6.640318	7.078895	7.37560092	7.395918	7.291529
tin + wet soil	60.6	70.6	75.8	99.9	102.8
tin + dry soil	58.5	66.7	70.1	90.9	92
moisture loss	2.1	3.9	5.7	9	10.8
tare	4.1	4.1	4.1	4.2	4.1
dry soil mass	54.4	62.6	66	86.7	87.9
% moist	3.86	6.23	6.21	10.38	12.29
dry density	0.651955	0.679509	0.708123669	0.683249	0.662147

Subgrade BH19-3					
	in^3	cm^3	m^3	mm^3	
volume of mold			9.9317E+13	99317	
sample mass (g)	3772				
Test no	1	2	3	4	5
water added (%)	0.04	0.06	0.08	0.1	0.12
mold + wet soil	7038.5	7138.3	7251.2	7286.9	7222.4
tare	5125.7	5125.7	5125.7	5125.7	5125.7
wet soil mass (g)	1912.8	2012.6	2125.5	2161.2	2096.7
wet soil mass (KN)	0.018758	0.019737	0.020844141	0.021194	0.020562
wet density (g/cm^3)	0.683264	0.718914	0.759242278	0.771995	0.748955
Unit Weight (KN/m^3)	6.70057	7.050171	7.445661247	7.570719	7.344774
tin + wet soil	121	43.8	81.1	100.6	119.2
tin + dry soil	115.8	41.2	75.3	92	107
moisture loss	5.2	2.6	5.8	8.6	12.2
tare	4.2	4.1	4.1	4.1	3.9
dry soil mass	111.6	37.1	71.2	87.9	103.1
% moist	4.66	7.01	8.15	9.78	11.83
dry density	0.652842	0.671819	0.702027072	0.70322	0.669726

Appendix B – 100% RAP Patching Mixture Laboratory Data

RAP Asphalt Binder Extraction Data

Sample	Mass of Test Portion (g)	Mass of water in Test Portion (g)	Mass of Extracted Mineral Aggregate (g)	Extra Mass of Filter Ring (g)	Moisture Content (%)	Asphalt Binder Content (%)
A	1000	0.357653791	940	3.1	0.04%	5.97%
B	1000	11.14186851	929	0.9	1.11%	6.05%
C	1000	0.864852399	945.2	1.2	0.09%	5.40%

RAP Aggregate Gradation Data

Sieve Analysis Sample A				
Sieve (mm)	Weight (g)	Cumulative (g)	% retained	%passing (%)
13.2	0	0	0%	100
9.5	90.6	90.6	10.19%	89.81
6.7	102.5	193.1	21.72%	78.28
4.75	67.7	260.8	29.33%	70.67
2.36	127	387.8	43.61%	56.39
2	27.7	415.5	46.73%	53.27
1.18	86.5	502	56.46%	43.54
0.6	119.5	621.5	69.89%	30.11
0.3	121.5	743	83.56%	16.44
0.15	83.5	826.5	92.95%	7.05
0.075	44.1	870.6	97.91%	2.09
Pan	18.6	889.2	100.00%	0.00
	889.2			
Initial Total Weight	890.9			

Sieve Analysis Sample B				
Sieve (mm)	Weight (g)	Cumulative (g)	% retained	%passing (%)
13.2	0	0	0%	100
9.5	74.3	74.3	8.50%	91.50
6.7	86.4	160.7	18.39%	81.61
4.75	65.3	226	25.86%	74.14
2.36	123	349	39.94%	60.06
2	27.1	376.1	43.04%	56.96
1.18	86.9	463	52.98%	47.02
0.6	122.3	585.3	66.98%	33.02
0.3	138.9	724.2	82.87%	17.13
0.15	91.6	815.8	93.35%	6.65
0.075	48.2	864	98.87%	1.13

Pan	9.9	873.9	100.00%	0.00
	873.9			
Initial Total Weight	874			

Sieve Analysis Sample C				
Sieve (mm)	**Weight (g)**	**Cumulative (g)**	**% retained**	**%passing (%)**
13.2	0	0	0%	100
9.5	110.5	110.5	12.25%	87.75
6.7	151	261.5	28.98%	71.02
4.75	101	362.5	40.18%	59.82
2.36	120.7	483.2	53.55%	46.45
2	25.6	508.8	56.39%	43.61
1.18	77.7	586.5	65.00%	35.00
0.6	97.1	683.6	75.76%	24.24
0.3	116.4	800	88.66%	11.34
0.15	67.5	867.5	96.14%	3.86
0.075	30.5	898	99.52%	0.48
Pan	4.3	902.3	100.00%	0.00
	902.3			
Initial Total Weight	903.3			

BBR Test Data

Sample ID	Temp (Degrees C)	Stiffness (MPa)	Deflection (mm)	M value
B	-12	128	0.608	0.323
B	-18	260	0.299	0.275
C	-12	156	0.508	0.304
C	-18	308	0.252	0.268