An Investigation on Micro-Trenching Technology for FTTH Deployment

by

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Abstract

The immense demand for Internet-based information sharing, entertainment, and communication services has dramatically augmented, and the existing copper network cannot meet this unprecedented bandwidth need. Upgrading copper-based networks to high capacity fiber optic (FO) networks involves high costs for deployment and has a negative impact on the existing infrastructures, surrounding environment, and nearby communities. Compared to other traditional methods, micro-trenching technology (MTT) in urban areas can facilitate a quick, easy, cheap, and low impact fiber-to-the-home (FTTH) deployment alternative. Communication providers (CPs) know MTT's potential, and they have completed several MTT projects in different countries. However, since MTT does not yet have any accepted construction standard, a poor quality installation is likely to be damaged or to damage the pavement. Severe weather conditions (e.g., freeze and thaw cycles) may cause further damages. Additionally, changes in weather conditions may yield significantly different backfilling performances. Therefore, before organizing a large-scale project, MTT needs to be evaluated in those conditions in order to ensure the durability of installations while maintaining the pavement's integrity, longevity, and aesthetic view.

To evaluate the performances of MTT in northern climates, two pilot installations using vertical inlaid fiber (VIF) technology and surface micro cabling inlay (SMCI) technology were installed in Edmonton, Alberta, Canada and monitored for over two years using optical time domain reflectometer (OTDR), ground penetrating radar (GPR) technology, and visual inspections. The OTDR results showed that the span losses were in allowable limit despite of sharp bends and traffic and weather distresses in the shallow-depth installations. The GPR and visual monitoring results from both installations showed significant vertical movements of conduit/cable and premature failures of backfilling materials, and a comparison of these installations concluded large

differences in movements and failures because of their discrete construction and material specifications. To improve the backfilling and overall performance of MTT, this study proposes a modified backfilling by stabilizing the conduit with a quick-setting and non-shrink grout in the base layer, while avoiding any damages that may occur during the road reconstruction and rehabilitation operations. Setting time, conduit coverage, flowability, and compressive strength tests were conducted in the laboratory to achieve conduit stabilization. All grouts had acceptable material properties, but only one was the most cost-effective. Considering the micro-trenching applications at freezing temperatures, the conducted modified compression test results showed that after full curing, the compressive strength of the grout was significantly reduced.

In the proposed backfilling, it is suggested that a cold mix asphalt (CMA) to be applied on top of the grout in the asphalt layer of the pavement. The CMA-1 (CMA) used in the VIF installation had premature failures, for instance, ravelling, cracking, edge disintegration, and settlement. In addition to the CMA-1, 11 other widely used CMAs, including proprietary and conventional mixes, were collected to test in the laboratory. By following sound construction techniques for the backfilling of micro-trenches, a high quality CMA, may provide not only good workability but also sufficient durability. The results of modified Marshall Stability and flow, indirect tensile strength, cohesion, and adhesiveness tests illustrated a high variation in material properties. Among 12 mixes, some of the CMAs would be good for patching and a few of them would be good for backfilling the MTT.

Preface

<u>Articles submitted to refereed journals:</u>

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Dedications

To

my parents, family, and friends

for their continuous support and love

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Chapter 1. Introduction

1.1. Background

Information communication technologies (ICTs) have become an inseparable part of every aspect of our society, including individual life, national economic growth (ITU 2003), business growth (ITGI 2003; Van Grembergen 2001), productivity improvement (Gordon 2000; Gilchrist et al. 2001; Devaraj and Kohli 2003; Gretton et al. 2004), sustainable development (Hilty et al. 2006), health, education, communication, and entertainment. The features of ICTs are transmitted and delivered to the end users through internet (Tranos 2013). Therefore, the recent demand for internet bandwidth has dramatically increased because of the unpredicted success and massive popularity of internet-based services, including real time video streaming, online video streaming (e.g., YouTube), file sharing, online gaming, high definition television (HDTV), and social media (e.g., Twitter, Facebook, Instragram) (Chen et al. 2010). The unprecedented bandwidth demand cannot be fulfilled through the existing copper networks since a copper cable has limitations in providing sufficient capacity and maintaining quality for long-distance services. The fiber optic (FO) network, however, can meet today's bandwidth need. FO cables theoretically have unlimited capacity (Saeed 2011), and they provide voice, video, and data services through a single cable at the speed of light while maintaining quality of services even over a long distance. Hence, communication providers (CPs) have been planning to gradually proliferate the bandwidth by abridging the existing copper cable lengths and by replacing copper cable with FO cable (Lannoo et al. 2008).

Currently, only 4.7% of Canada's total broadband subscriptions are fiber connections, and only 18% of the broadband connections are higher than 15 Mbps (OECD 2014). Therefore, to fulfill the rising demand for bandwidth, Telus Communications Company, similar to other CP companies in Canada, has planned to upgrade their existing copper network to a fiber network. As an illustration, Telus has decided to migrate from a copper network to a FO network in Edmonton in order to deliver services at 150 Mbps speed to 90% of homes (more than 300,000 homes) by 2021, spending $1 billion (Mah 2015). However, constructing FO networks draws serious economical, legal, environmental, and social issues that have to be considered and resolved prior to the installations.

When the FO network construction projects are conducted inside a city to connect residential, business, and industrial areas, these projects are usually found to be very difficult and more challenging than previously thought (Stojicic 2002). For example, the civil work costs of the construction could be 60% to 70% of the initial investments (Casier et at. 2009), and these operations involve disruptive digging on the streets (Stojicic 2002). The digging operations increase the risk of damaging existing services and the cost of community disturbances; where underground spaces are overcrowded, the impacts on the environment are substantial (OECD 2014; Atalah et al. 2002), restoration and traffic control costs are high, pavement damages are significant (Atalah et al. 2002), and neighbourhood disturbances are notable. Therefore, for network construction, obtaining permits and agreements is often found to be difficult and time consuming (Jeyapalan 2003). Additionally, the local government sometimes imposes legal difficulties and zoning laws (OECD 2014). Regardless, the extent of impact due to FO deployment depends on the choice of installation method.

Generally, the FO deployment method can be classified into two major groups: direct buried and utility sharing methods. A direct buried method involves direct subsurface installation of FO cable. An example of a direct buried method is open–cut, which has a high risk of hitting existing underground services (OECD 2014), high costs of traffic detours, adverse impacts on the pavement (e.g., long-term), and significant impacts on the air and sound quality (Atalah 2002; Jeyepalan 2003). Therefore, to reduce the costs of FO deployment and its associated impacts, trenchless and near-trenchless methods, such as plowing, mini-trenching, micro-trenching, piercing or mini-horizontal directional drilling (mini-HDD), can be an effective tool (Savage 2005).

In utility sharing methods, the FO cables are installed using the existing utility networks (e.g., sewer, water or gas lines), which require an intensive collaboration between the utility owner and the telecom companies (Gokhale 2006). When a FO cable is installed in a utility network, it may be affected and damaged during the maintenance, renovation, and replacement operations of that network (i.e., sewer, water, and gas). As a result, an innovative, convenient, and reliable method is increasing in popularity as an alternative option for FO deployment.

To ensure FO deployment occurs at low costs and with fewer impacts, a potential alternative for urban FTTH connections can be micro-trenching technology (MTT) (Griffin 2012; ITU 2003), which requires no utility inspection due to its shallow depth of installation. MTT does not disturb or damage the adjacent subsurface facilities (DCMS 2011), and it causes minimal traffic delays and low environmental and social impacts (Chorus 2011). MTT is found to be 30 times faster and five times less costly than the conventional open-cut method, and the micro-trenches are difficult to recognize when reinstated properly (McDonnell 2009). MTT also poses less risk to underground services than mini-HDD and requires narrower trenches than mini-trenching (Stahlbrand 2012).

1.2. Research Motivation

MTT can create alternative options for laying FO cable on roads and sidewalks with minimal disturbances and at reduced costs, when traditional methods fail to accomplish. As a result, communication providers (CPs) used this method to complete several trial projects applying different construction and material specifications. After completing these installations, many CPs claimed MTT was a successful deployment method on asphalt pavement. However, most municipalities have not yet been convinced to issue a permit for this method because of its poor quality of reinstatement, lack of deployment standard, and unsolved liability risks of road and/or FO cable damages (DCMS 2011). Additionally, in changed weather conditions (e.g., freeze and thaw cycles), MTT may result in significantly different backfilling performance, leading to premature failures of restoral materials which may in turn degrade the present serviceability index (PSI) of pavement (Arudi et al. 2000; McDonnel 2009). Moreover, a conduit/cable exposed to freeze-thaw conditions may experience movements/displacements toward the pavement surface, pushing to the zone (depth) of the pavement rehabilitation and reconstruction (Duraline 2016).

Most of the CPs' trialed MTT projects were conducted in climate conditions that are significantly different from the climates of Alberta (Canada). The field monitoring and performance evaluations of these installations were not conducted, and no follow up research work was done to improve MTT and satisfy all the involved parties. Furthermore, the performance of a MTT installation in cold regions is still unknown. In order to meet the demanded standard of a MTT installation when applied in cold regions, it has to be thoroughly evaluated in the laboratory as well as in the field.

As backfilling performances in a narrow and shallow micro-trench may vary with the change in weather conditions, the trench restoration in northern climates has to be durable and cost-effective.

Because of the narrow size of the trench, any material applied in the micro-trenches has to be highly workable, compactable, durable, and economical. Considering environmental conditions, the laboratory evaluations on backfilling material can be helpful for increasing the durability and performance of MTT in cold regions.

1.3. Research Objectives and Scopes

Considering the gaps in previous literature, four objectives have been set in this thesis.

Objective 1: To comprehensively study the existing FO deployment methods, including applicability and pros and cons. This research especially focuses on MTT for building a FO network and the advantages, preferences, limitations, challenges, and scopes of this method.

Objective 2: To monitor and analyze the performance of pilot installations in Edmonton using different MTTs.

Objective 3: To improve the performances of MTT installations by proposing a modified backfilling method based on the field monitoring results and the laboratory investigations.

Objective 4: To evaluate the properties of various cement grout and cold mix asphalt materials as part of improving MTT backfilling.

The comprehensive literature review will give a big picture perspective about the constraints and challenges of different FO deployment methods in an urban environment. It will also lead to a clear understanding of the scope of this research and the potential for MTT to provide an efficient (e.g., low costs and impacts) FTTH rollout. The trial installations of MTT in cold climatic regions (e.g., in freeze-thaw conditions) while experiencing traffic-related distresses will give a clear understanding about the field performance of FO, conduit/FO cable, and backfilling materials. These installations will also create an opportunity to measure the seasonal movements (if any) in FO cable's positions due to the freeze and thaw cycles and traffic loads. The proposed modified backfilling in this study is expected to yield a better performance since it is designed in consideration to field results, standards, recommendations, and case studies. A series of laboratory tests on proposed backfilling materials will demonstrate their effectiveness and feasibility. As part of the proposed backfilling section, CMAs will be tested for evaluating and comparing mixture properties. These test results can be equally relevant for other applications and will be helpful for future research and planning.

1.4. Research Methodology

This thesis is organized into three sections following the research methodology that is undertaken in three stages. In the first stage, a comprehensive literature review summarized the applicability, limitations, advantages, and disadvantages of traditional FO deployment methods. Giving special attention to MTT due to its high potential, this study carefully reviewed the MTT installation preferences, existing challenges, case studies, and available backfilling materials, particularly CMA due to its high potential to be used for this purpose.

In the second stage of this research, two pilot installations using two MTTs, vertical inlaid fiber (VIF) technology and surface micro cable inlay (SMCI) technology, developed by the TeraSpan Networks Inc. and JETT Networks, were deployed in Edmonton. These installations were monitored using optical time domain reflectometer (OTDR) technology, ground penetrating radar (GPR) technology, and visual inspection to measure the fiber performances, the FO cables' movement in the trench, and the backfilling materials' performances in cold weather conditions and under traffic loads. After analyzing the field monitoring results, a modified backfilling was proposed to improve the trench restoration of the MTT. The proposed backfilling method recommends applying grout to stabilize the conduit/cable in the base layer of the pavement. The setting time and coverage around the conduit of three grouts were measured in the laboratory, taking into consideration the nature of the MTT and the underlying objective of grout application. Also, the compressive strength (ASTM C109/C109M-13) of grouts were tested. In addition to following the regular procedure for compressive strength test, the grout samples were made frozen before happening the complete hydration so that the reduction in compressive strength can be measured when applied at freezing temperatures.

For the third stage of this research, among the MTT pilot-installations backfilling materials, the quality of CMA as observed in the field had a significant role in the micro-trench performances. For this reason, the CMA used in VIF technology along with 11 other different types of CMAs and a hot mix asphalt (HMA) were evaluated in the laboratory. Some of the CMAs were high performance proprietary cold mix (PCM), and others were conventional cold mix (CCM). Both PCMs and CCMs are consisted of open-graded (OG) and dense-graded (DG) aggregates. Four laboratory tests, including modified Marshall Stability and flow (ASTM D6927-06), indirect tensile strength (AASHTO T283-14), cohesion (AASHTO TP44-94) and adhesiveness (developed by the Virginia Department of Transportation) tests, were conducted on all asphalt mixtures. For the first two tests, in addition to the regular test procedures, a curing step was added by following the procedure reported in SHRP H-353 (Wilson and Romine 1993) and by EBA Engineering Consultants Ltd. (2011). The test results of 12 CMAs were compared with the HMA mixture, as well as with the given recommendations.

1.5. Structure of the Thesis

The thesis has the following organization:

Chapter 1 – Introduction: In this chapter, introduction, background of the study, research motivation, objectives and scopes, methodology, and thesis arrangement are provided.

Chapter 2 – Literature Review: In this chapter, importance, present condition, economic impact, and deployment constraints of broadband are briefly discussed. Various FO deployment methods encompassing applicability, advantages, disadvantages, and limitations are briefly but comprehensively discussed. Also, the introduction, process, advantages, and case studies of MTT are concisely presented. The installation preferences and existing challenges of MTT are elaborately discussed. The restoring materials for micro-trenches, focusing on applicability, pros and cons, are presented. Cold mix materials' properties, distress modes (at different stages), and previous studies are summarized.

Chapter 3 – Field and Laboratory Investigations on Micro-Trenching Backfilling for FTTH Deployment: In this chapter, the pilot installation details, backfilling material specifications, and monitoring and observation data are presented. A modified backfilling has been proposed based on the field investigation and installation requirements. In addition, the grout properties and functions, such as bonding between grout and conduit, setting time, flowability, and compressive strength, are tested and presented. Also, the laboratory tests on CMA-1, a VIF backfilling material, is conducted and compared with a hot mix. The conclusions of field and lab work are summarized.

Chapter 4 – Laboratory Investigation of Cold Mixes for Cold Region Applications: In this chapter, a brief introduction, advantages, and disadvantages of cold mixes are presented. Previous studies on cold mixes and their materials' properties are discussed. The significance, use, and procedure of laboratory tests (e.g., Marshall Stability, indirect tensile strength, cohesion and adhesiveness) are presented for evaluating mixture properties such as stability, moisture susceptibility, cohesion, and adhesiveness. The test results are compared with a HMA mixture, and the discussions on comparison are summarized in the conclusion.

Chapter 5 – Summary and Conclusion: In this chapter, research findings and results are summarized. The major conclusions of this study are concisely discussed. Also, the limitations of this study and recommendations for further research are provided.

Chapter 6 – References: In this chapter, all the references are listed.

Chapter 2. Literature Review

2.1. Introduction

This chapter discusses the benefits and applications of having a high-speed internet network and the obstacles and limitations towards building this next generation network (NGN). To construct a NGN, applicability, advantages, and disadvantages of various FO deployment methods are concisely but comprehensively presented. Studying the available literature of micro-trenching technology (MTT), including reports, advice notes, standards, and previous case studies, has given a clear understanding about the installation preferences, existing challenges, and available backfilling material options. The installation preferences of MTT agreed upon by municipalities and internet service providers (ISPs) should be followed and maintained during planning and execution stages. In addition to MTT preferences, the existing challenges, such as reluctance to issue permits and agreements, bottlenecks in construction and backfilling, impacts of severe weather, and risks of sharing liability, have made this method less acceptable and less practised. However, after acknowledging MTT preferences and its existing challenges, the main concern is the quality of backfilling; different restoral options are discussed in this chapter. As a potential backfilling option for MTT, the properties, problems, and previous research of cold mix asphalt (CMA) are carefully studied and presented.

2.2. FO Deployment for High-Speed Broadband

Although internet operators in the past used to relay on discrete technical specifications (i.e., separate networks) for transmitting voice, data, and video services, broadband technology has enabled a simultaneous transportation of these multiple signals and traffic types. Currently, a single digital internet protocol (IP) of a broadband network can provide these services as well as many other services (OECD 2014). For instance, a broadband connection can be used for communications between companies and individuals using telephony and telepresence, and for gaming, video surveillance, etc. (Forzati and Mattsson 2011). The transmission mediums for a broadband network usually are coaxial cable, twisted pair, FO cable, and wireless technology. The traditional copper network made of coaxial and twisted pair has limited capacity and cannot maintain the desired quality during long-distance transmissions. As a result, the bandwidth demand has greatly increased for delivering high-quality and emerging internet services. To overcome the limitations of the copper network, a fiber network based on optical fiber technology, claiming theoretically unlimited bandwidth capacity, has become a global solution for meeting the existing and future demands of bandwidth. This network allows quick file transferring, high-definition (HD) video streaming, high-quality real-time communication, and multitasking (Atkinson et al. 2009).

Many countries have undertaken long-term plans for developing a fiber network (i.e., fiber-to-the-home [FTTH] connection) to have NGN, but several factors such as capital expenditure, transit costs, and municipal obstacles adversely affect these plans (OECD 2014). The first and fundamental challenge for replacing the existing copper networks with fiber to construct a FTTH network is high fixed costs; however, by having an advanced deployment technique and ensuring a high take rate in a dense neighbourhood, the fixed costs can be reduced significantly (OECD 2014). Besides the construction costs of a FTTH network, the present conditions of the transit and backhaul networks, the second most important factor, determine the costs for the NGN. But if transit and backhaul networks already have the fiber optic (FO) cables, the NGN (e.g., FTTH) deployment costs will be relatively low. The third factor is obstacles usually imposed by municipalities due to their policies and resistances; these play a vital role in FTTH construction because, in the case of some FTTH deployment methods, ISPs must dig up streets and use overhead power lines or existing utilities (e.g., sewer, water, gas pipes). Unfortunately, local authorities are reluctant to issue these permits and agreements, which delays or sometimes even cancels a project (OECD 2014). Hence, new methods for FTTH network construction are gaining popularity because they minimize the obstacles imposed by local governments as well as overall deployment costs.

2.3. FO Deployment Methods

The major FO cable installation methods for NGN as shown in Figure 2-1 can be categorized in two main groups: direct buried and utility sharing methods. The direct buried methods can be further classified depending upon the requirements for trenching; the utility sharing methods for FO cable are divided into two types based on the location of the existing utilities: overhead utility and underground utility. In addition to these main groups, the duct sharing and cable de-coring methods can also be used in certain conditions.

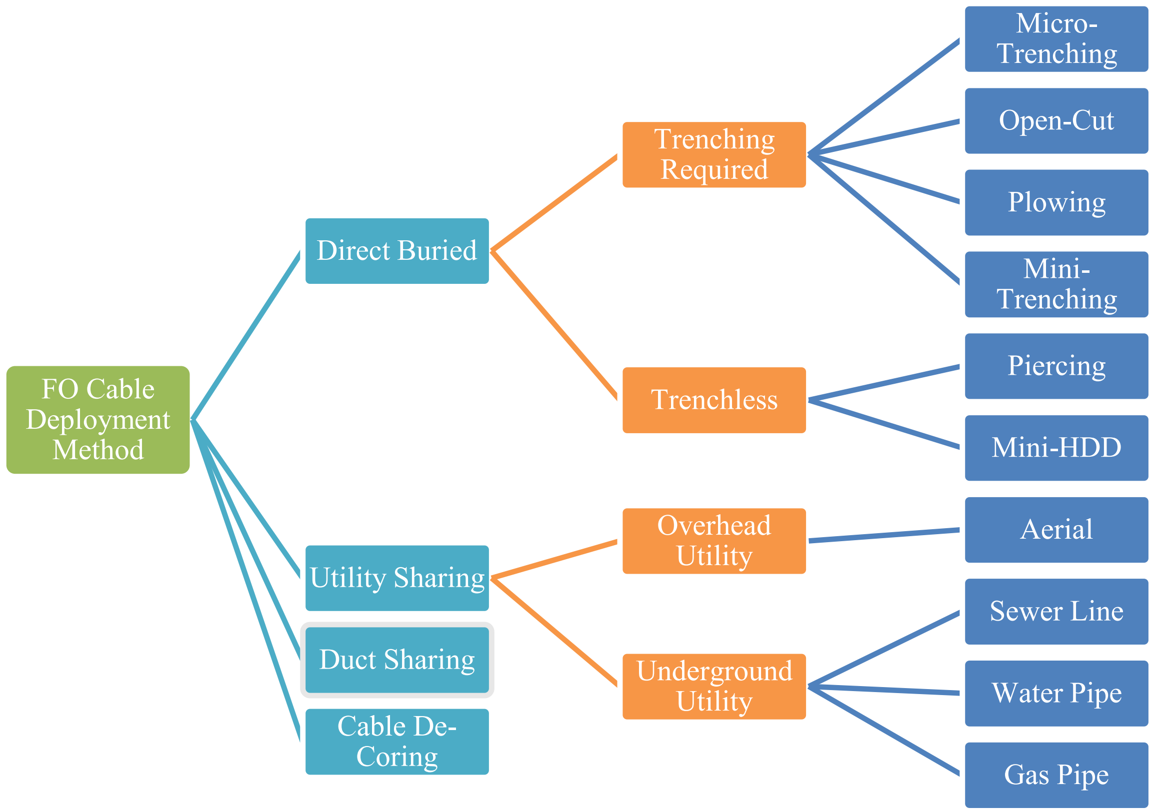


Figure 2-1: FO network deployment methods

The following sections elaborately discuss the applicability, process, advantages, and disadvantages of these methods.

2.3.1. Open-Cut

The traditional open-cut method for FO network construction consists of excavating a 30–60 cm wide trench, laying conduit(s) in the trench, and refilling and reinstating the original surface (CSMG 2010).

Open-cut can be an alternative method for deploying FO cable in areas where excavation is easy, utility inspection and protection are not required, economic and environmental impacts are small, restoration costs are low, the water table stays below the trench depth, and shoring during the excavation is not needed (Atalah et al. 2002).

As open-cut in metropolitan business districts requires special attention for locating and protecting other services, the overall productivity goes down, resulting in high construction costs. Open-cut deployment in landscaped and paved areas, therefore, involves high restoration costs and relatively high impacts on the economy, environment, and community. Despite that, the costs of open-cut may become even higher as a result excavating in rocky layers and below the ground water table where shoring is required. Besides the high costs and construction challenges, open-cut may impair the integrity and longevity of the pavement (Atalah et al. 2002).

2.3.2. Plowing

Plowing is more useful than the open-cut method for long-distance Greenfield applications since it involves less destruction of soils (Cables Plus 2012). The plowing method creates a smaller ditch than open-cut, places FO cable inside the trench, and restores it at the same time with already excavated materials. Plowing is inapplicable in brownfield areas since it has a high chance of hitting the subsurface utilities.

2.3.3. Mini-Trenching

Mini-trenching is significantly narrower than open-cut, but it is much wider than MTT. This method is recommended for laying FO cable on routes where the soil subgrade is sandy, gravel, or contains medium-sized cables (10–20 cm diameter) and the excavation depth does not interfere with existing underground utilities (ITU 2003).

The main advantages of mini-trenching over open-cut are a relatively faster excavation, lower costs, and relatively lower environmental and social impacts (ITU 2003). In contrast, when comparing trenchless and near-trenchless methods, mini-trenching has higher restoration costs, project duration, and environmental and community disturbance.

2.3.4. Mini-Horizontal Directional Drilling

Mini-horizontal directional drilling (mini-HDD) has become a powerful tool for deploying the last-mile FO cable (e.g., FTTH) where open excavation is not permitted or possible. It can be an alternative solution for FTTH to cross distances of less than 500 ft and for deploying conduits less than 2 in. in diameter since mini-HDD can work in tight urban conditions (Orton 2006).

According to Orton (2006), mini-HDD causes significantly less social and environmental impact. However, in urban areas where there is a high risk of hitting utility lines, the installation costs increase when a detailed inspection must be done to locate utilities. Additionally, the drilling fluid leakage may elevate the construction costs.

2.3.5. Piercing

Piercing aided by an impact mole or pneumatic tool is commonly used for crossing short- to medium-range distances (e.g., 30–50 ft), such as driveways, roads, sidewalks, and other improved surfaces (i.e., paved and grass surfaces) (Ditch Witch 2010).

Piercing connects last-mile fiber, causing minimal disturbance to the end users. It is applicable where high installation accuracy is not required and when the cost of mini-HDD is too much (CSMG 2010). For the FTTH installations, piercing requires a relatively low investment on the equipment (Ditch Witch 2010) and a minimal crew composition in the project completions (Orton 2006). In contrast, piercing does not have steering and tracking facilities, which may lead to utility damage (CSMG 2010).

2.3.6. Aerial

The aerial method installs FO cables in residential areas using existing power line poles. Since it does not require any kind of digging, the aerial method is quick and easy. Currently, implementing the aerial method in newly developed areas has been found difficult since most of these areas do not have any overhead power lines (OFS 2013). Moreover, this method requires permits and agreements with municipalities or local authorities; this may result in a time-consuming process since authorities are sometimes reluctant to issue a permit or agreement.

2.3.7. Utility Sharing

Existing underground infrastructures such as sewer, water, and gas networks may be utilized to host FO cables, creating a low cost and environmentally friendly construction technique.

In man-entry sewers, the cables are manually installed to connect the main parts of a city; in non-man entry sewers, the cables are installed in the distribution networks using robotic technologies, for instance, a sewer access module, sewer telecommunication access robot, cable runner technology, and lining technologies (Gokhale 2006). Furthermore, the water and gas pipes could be another way of sharing utilities to build a FTTH network (FTTH Council Europe 2014).

The utility sharing methods have a smaller economic, environmental, and social impact with minimal restoration costs and no risk of damaging existing utilities (Gokhale 2006). In the case of sewer networks, the installed FO cables can improve the sensing and surveillance system of the sewer pipes (Jeyapalan 2003). But this installation must be designed in such a way that the flow capacity of a sewer line and the traditional cleaning methods used by the utility owners should not be comprised. Additionally, the materials used for the installation must survive the adverse environment of a sewer network (FTTH Council Europe 2014). Before using these utility networks, an intensive collaboration between utility owners and ISPs is necessary to determine the feasibility and implementation of the project.

2.3.8. Duct Sharing

In the duct sharing method, the already installed ducts or conduits are shared with other telecom service providers for FO cable deployments. Sharing these ducts or conduits can significantly drive down the FTTH rollout costs of incumbent telecom operators, but well-defined duct sharing and accessing rules are required, which is sometimes difficult to do (FTTH Council Europe 2014).

2.3.9. Cable De-Coring

The cable de-coring method has created an opportunity to replace copper cable with FO cable without excavating the full length. For this operation, two pits are dug 50–400 m apart, and a specialized biodegradable fluid is pumped between the core and the outer cable sheath in order to mechanically retrieve the copper cable and replace it with a fiber cable (FTTH Council Europe 2014).

Cable de-coring is 40–90% cheaper than new installations and requires substantially less time and money. But it is only applicable for replacing larger diameter (more than 25.4 mm) copper cable (FTTH Council Europe 2014).

2.3.10. Micro-Trenching Technology

Micro-trenching technology (MTT) is an alternative and emerging method for building FTTH networks in urban areas where other direct buried methods are either inapplicable or have a high impact on traffic, community, and costs (ITU 2003). In MTT, trenches are typically 2 cm wide and 12–30 cm deep for placing FO cable or sometimes conduit without disrupting or damaging existing underground services (DCMS 2011).

MTT causes minimal traffic disruptions, noise, and overall impacts to community areas (Chorus 2011). Before and during MTT installations, inspections and protection for other utilities are not needed because cables are placed well above the depth of existing underground facilities. MTT has been found to be thirty times faster and five times less costly than traditional open-cut methods, and the trenches are difficult to see when reinstated properly (McDonnell 2009). MTT leaves fewer construction footprints than mini-trenching (Stahlbrand 2012).

A MTT installation mainly consists of three major steps as illustrated in Figure 2-2.

Trench Cutting — Conduit Placing — Trench Restoring

Figure 2-2: MTT process

In the first step, micro-trenches are dug along the marked line by using a specified trenching equipment, as shown in Figure 2-2. The trench cutting process can be in either dry conditions or wet conditions, depending on the requirement of water use. Trenching is always preferable in dry conditions since the cleaning process using a dry vacuum cleaner is easier, resulting in dry and mud-free trenches. Trenching in wet conditions may cause water stagnation in the trench and mud-covered trench walls. Hence, after wet trenching, ITU (2003) recommends a high-pressure water jet for cleaning the trench and a compressed air or blowpipe for drying it. Sometimes, a trench with sharp corners or bends must be beveled with a hand saw to ensure the allowable bend radius of FO cables (ITU 2003).

The second step is placing a conduit/cable inside the cleaned trench. Duraline (2016) reported that the conduit/cable should be placed in and pushed to the trench bottom in order to have maximum coverage on top of the cable. In some cases, when flowable fills (e.g., grout) are used for trench restoration, the cables may need to be fixed with spring clips against the buoyant force (Duraline 2016).

The third and final step of MTT is restoring the trench to its original state. Since sufficient compaction and the compaction temperature in small micro-trenches cannot be achieved and maintained, a hot mix asphalt (HMA) may not be feasible for micro-trench reinstatement. Conversely, hot bitumen, according to ITU (2003), is a feasible reinstatement option for this method, and it can be applied utilizing a proper sized nozzle (ITU 2003). There are other backfilling materials, and the main functions of these backfilling materials are to provide mechanical and thermal protection to the FO cable and to prevent water ingression into the trench (ITU 2003 and Duraline 2016).

2.4. MTT Case Studies

Communication providers (CPs) have used several MTTs in different locations applying different trenching techniques and restoring materials and procedures.

In 2011, a pilot installation was finished in Lower Hutt, New Zealand, in order to study the feasibility and productivity of MTT and mini-trenching methods. For MTT, trenches were dug on three different types of surfaces, for instance, asphalt surfaces on roads, concrete surfaces on sidewalks, and grass surfaces in grass berms with trench dimensions of 8 cm × 43 cm, 5.5 cm × 23 cm, and 5.5 cm × 23 cm, respectively. The respective installation lengths on these surfaces are 505 m, 348 m, and 130 m. To backfill the trench on the asphalt and concrete surfaces, a self-compactable, re-excavatable, and quick-setting mortar was used, the maximum aggregate size and compressive strength of which were 4–5 mm and 1–3 MPa. When applied mortar gained its strength (after 60–100 min of application), vehicles and pedestrians were allowed to cross over the trench. As a final backfilling layer, HMA was applied, which required milling out of the trench's already hardened mortar in order to create a 2.5–3 cm × 40 cm ditch (Chorus 2011). This additional milling process produced heavy dust, sound pollution, and prolonged traffic detours, and it might have compromised the structural integrity of the pavement. For backfilling the sidewalk MTT, a concrete mixture was used; however, Chorus (2011) reported that the local authority was not satisfied with the standard of backfilling (Chorus 2011). The trenching processes encountered several service line damages (e.g., water, storm, etc.) (Chorus 2011).

In George Town, Cayman Islands, a pilot MTT project (5.18 km long) was finished in just four months by only working at night to avoid disturbing the island's visitors. A conduit (4-inch tall) was placed in the 1.9 cm × 30.5 cm trench (3.96 km long), and two of the same conduits were deployed side by side in the 2.4 cm × 30.5 cm trench for the rest of the length; in both cases, the conduits left an 8-inch cover that can easily avoid the future road reconstruction depth (4–6 inch). For trench restoration, beach sand was applied and filled the bottom (4-inch) of the trench, followed by a compacted cold mix at the top (Schultz 2011).

MTT was used successfully in Australia for the national broadband network in brownfield multi-doweling units for both businesses and homes in 2014. Micro-trenches 1.3-cm wide and 25-cm deep were dug on the asphalt and concrete surfaces, followed by placing a vertical deflecting conduit (VDC) into the slot and filling the trench with either a cold mix or a bitumen seal (Ralston Churchill 2014). Also, GM Plast was involved in testing MTT in Ireland, Germany, France, Norway, Portugal, Israel, Malaysia, and Iran; they have more than 25 km of finished projects and are planning more. Among their finished projects, the Tjome project (2.0-km long) in Norway connected 113 homes using MTT on the street (GM Plast 2014). However, no performance evaluations or monitoring results are available for these projects.

2.5. MTT Preferences on Asphalt Pavement

The parties involved in MTT installations (i.e., local and highway authorities and ISPs) prefer to have a standard procedure for trenching, cabling, and backfilling.

2.5.1. Trenching

The Department for Culture Media and Sports (DCMS) published an advice note on MTT, which mentioned suitable road types for the installation, preferable trench location on the road, and desired trench depth in asphalt pavement (DCMS 2011).

According to the DCMS (2011), any type of MTT deployment will depend on the types and compositions (layers) of roads. In some road types, such as concrete or evolved rural roads in particular, the trenching operation may damage the long-term integrity of the road. Therefore, a suitable road for MTT installation has to have a well-defined road base, binder course, and surface course. In addition to the types and compositions of roads, the location of existing infrastructures in the road and the depth of micro-trenches determine the feasibility of this method. The depth of MTT should not intersect or go close to the subsurface facilities (DCMS 2011).

The position of a micro-trench on the road is another key consideration, with the greatest risks of problems arising when the trenches run in defined wheel paths. Hence, micro-trenches are most often dug toward the curbside of a road, and the trench restoration should not have any impact on the cyclists and motor cyclists (DCMS 2011).

The trench alignment should be as straight as possible, and in case of bends, the bend radius of a FO cable should not exceed its allowable limits (ITU 2003 and DCMS 2011).

The trench depth on a road, recommended by ITU (2003), should not be less than 7 cm without penetrating past the asphalt layer (ITU 2003). Conversely, DCMS (2011) recommended a minimum of 17.5 cm of trench depth on a road, which has a minimum of 32.5 cm of bound layers (DCMS 2011).

2.5.2. Conduit/Cable Placing

The main function of a conduit or cable that carries FO is to provide mechanical protection and temperature resistance in micro-trenches (ITU 2003; DCMS 2011). As it is deployed in a shallow depth on the road, the crushing resistance of a cable should be enough to resist the damages caused by traffic loadings. As well, the thermal resistance of a cable should be strong enough to withstand the heat exerted by the hot bitumen or HMA during the road reconstruction or rehabilitation processes. When a cable passes a sharp bend, the bend radius of the cable should not cross the allowable limit as specified by the manufacturer (ITU 2003).

2.5.3. Backfilling

According to ITU (2003), after placing a conduit/cable inside the trench, a retaining strip (an expanded polyethylene strip) fixes it to the trench bottom, followed by a free-running and highly water-repellent filling material (e.g. rubber strip). The rubber strip is wider than the micro-trench and provides both mechanical and thermal protection (ITU 2003). A final restoration material such as hot bitumen, HMA, cold asphalt, or grout may fill the rest of the trench.

Besides providing a stable surface to vehicular loadings on pavement, a backfilling material keeps additional moisture away from the pavement base layer. If the material fails to intercept the moisture infiltration through the backfilling, the trench restoration as well as the road conditions may get affected over time. Additionally, a severe cold climate may worsen this condition. Hence, to avoid water ingress through a restoral material, a strong bonding between the backfilling material and the original pavement surface is always desirable (Duraline 2016).

Therefore, a restoration material used in MTT should meet the specification provided by the local and highway authorities. This specification must follow a design procedure with traffic loading and weather conditions similar to those of HMA (DCMS 2011). The specification designed for the micro-trench backfilling could be different based on the pavement types (e.g., flexible and rigid). For flexible pavement, the backfilling materials are expected to be flexible, impermeable, flowable, stable, self-compacting, rapid hardening, safe and simple to use. For rigid pavement, in addition to these properties, the materials must be quick setting (Stirling Lloyd Polychem Ltd 2011).

2.6. MTT Challenges

Since MTT is a new and shallow installation method on the roads, it has not yet been intensively investigated in order to be accepted by local and highway authorities and ISPs; thus, many concerns for this method exist. The main challenging issues of MTT are permits and agreements, construction, restoration, adverse weather conditions, and documentation and liability.

2.6.1. Permits and Agreements

Materials for utility-cut backfilling, including the innovative ones, need to be evaluated to assess the influence of seasonal weather variations on performance. Besides materials, various available construction techniques must go through the evaluation and comparison process (Zeghal and El Hussein 1984).

Considering material specifications to be adequate, CPs around the world use different backfilling materials for the MTT. As a result of that, the CPs always negotiate with local and highway authorities since the reinstatement specification is not covered in the Code of Practices (DCMS 2011). Also, no construction standards are available for this method. Most of the authorities perceive MTT to be a construction technique that is very difficult to manage due to its high damage potentiality and high liability sharing risks while reconstructing or resurfacing the pavement (McDonnel 2009). Therefore, municipalities are often reluctant to issue permits and agreements for MTT on their roads (DCMS 2011).

2.6.2. Construction

On some road types, MTT may not be feasible since surface reinstatement might not preserve the long-term integrity of these roads. The trenching operations on the roads which aged over centuries may disturb the structural matrix of the pavement that may result in speedy deterioration of these roads. Applying this method in a rural road built of granular materials can be challenging, and it may result in aggregate congestion in the trench, hindering the overall trench cleaning. Therefore, it is more appropriate to employ MTT in a road or sidewalk, which has a well-defined compact base (ITU 2003; DCMS 2011).

However, micro-trench construction that crosses sidewalks to directly connect individual users may increase the risk of pedestrian accidents and liability sharing (DCMS).

The choice of MTT methods has significant influence on the quality of installation since it determines the level of difficulty in trenching and cleaning. Also, the ease of construction and the quality of backfilling may differ from one MTT method to another. For instance, using water during trenching may affect the adhesiveness of the restoral materials. That is why after trenching in wet conditions, it is recommended the trenches be dried. However, a dry trenching method is always preferable (Duraline 2016). Additionally, the type of saws used for trenching and the equipment used for compaction may have direct impacts on the installation performance.

Micro-trenches have straight sides and smooth surfaces, which are similar to the hole created to repair cracks in asphalt pavement. In case of crack repairing, Roberts et. al (1996) recommended a tack coat on the smooth surfaces and sides in order to increase the adhesion between the HMA and the existing asphalt surfaces. However, the micro-trenches are very narrow compared to the hole made in crack repairing, making the HMA as well as any tack coat application very difficult. Although the smooth surfaces can provide good adhesion in the presence of tack coat, they do not create sound mechanical interlocking with the patching materials (Roberts et al. 1996). Obtaining this mechanical interlocking in MTT will be difficult since the saws used for trenching do not create uneven surfaces.

2.6.3. Restoration

The backfilling quality of a utility-cut plays an important role in the present serviceability index (PSI) of pavement and the performance of that installation. For instance, poor backfilling after a direct-buried installation significantly affects the long-term performance of a road, and as a result, premature failures within and around the utility-cut result in increased maintenance costs (Peters 2002).

The main causes of backfilling failures are construction methods, backfilling materials, trench locations, climate, traffic, and pavement conditions (SUDAS 2005 and Widger 2013). For example, a lack of sound construction methods during an excavation may disturb the trench wall and its materials, leading to a loss of control over density during the placement of backfilling materials (Widger 2013). A material with inappropriate properties may affect the performance of restorations. If possible, a trench on the road should be located outside of the wheel path because traffic load, moisture, and improper compaction may accelerate the pavement failures (Widger 2013).

As micro-trenches are much narrower and shallower compared to other utility-cuts, the impact of trenching on the road may be significantly less than other utility-cuts. Although the negative effect of trenching on the roads may be low, the quality of trench restoration will be key for a durable installation. However, the durability of this installation may be affected by the pavement rehabilitation process and the freeze and thaw cycles (McDonnel 2009).

Since the performance of a MTT installation is mostly dependent on the properties of the restoral materials, CPs tried different backfilling materials to confirm the compliance of local and highway authorities. Generally, an inadequate fill or compaction leads to poor bonding of the backfilled materials. With sufficient filling and compaction, the restoral materials should form a good bond with the original pavement surfaces to ensure a sound insulation against the water intrusion. Thus, this insulation will help preventing the tendency for backfilled materials to be out of the trench (Duraline 2016).

2.6.4. Adverse Weather Conditions

In cold regions during winter, frost induces additional distress around the utility-cut, and the thawing process in spring causes differential settlement of the pavement around the utility-cut. These phenomena in freeze-thaw conditions need to be incorporated into the current designs and evaluation methodologies of trench restoration. Likewise, the MTT installations in North America face frequent freeze and thaw cycles that result in frost-heave and settlement, requiring more robust bonding materials for the backfilling. A poorly bonded material will allow water to penetrate into the micro-trench, which could lead to the aforementioned phenomena and leave the trench exposed (Duraline 2016).

2.6.5. Documentation and Liability

As it is sometimes difficult to trace, a MTT installation may lead to a risk of liability sharing. This is due to the damage that may happen to the pavement and FO cable when utility installations (e.g., by other CPs and for other services) and road maintenance activities (e.g., resurfacing and reconstruction) are performed. Hence, the municipalities are often reluctant to issue a permit for any of these projects (DCMS 2011). ITU (2003) recommended having clear documentation showing layout and depth to reduce the probability of damage and to increase the acceptance of municipalities.

2.7. MTT Equipment

Husqvarna has a wide range of floor saws to make trenches in a variety of depths and widths on asphalt or concrete surfaces. These saws operate using a water flow during the cutting operations in order to keep the blade temperatures low. As debris and mud-water settle in the trench, a spoil removal system assisted with a wet vacuum cleaner is required. Even though Husqvarna saws do not have any integrated system for trench cleaning, they have a completely separate spoil collection system (Husqvarna 2015).

Figure 2-3: Floor saw for MTT (Husqvarna 2015)

Ditch Witch has designed an advanced piece of trenching equipment (i.e., the MT12) for MTT on asphalt pavement. The MT12 can precisely cut narrow trenches (1.9–3.2 cm wide and 16.5–31.8 cm deep) on asphalt concrete in congested urban areas using a specially designed diamond blade while ensuring high efficiency. Since the MT12 is capable of cutting in dry conditions, the spoils are dry and mud-free. A separate dry vacuum excavation system (i.e., FX 60) is attached with the MT12 cutting system so that the cutting debris can be collected simultaneously from the trench (Ditch Witch 2010).

Figure 2-4: MTT equipment of Ditch Witch (Ditch Witch 2010)

Marais has also developed two advanced machines (i.e., Cleanfast and Meteor) for MTT on asphalt and concrete pavement surfaces. Unlike the Husqvarna floor saw and Ditch Witch MT12, Marais MTT machines have a simultaneous cutting, cleaning, and spoil collection system. The Cleanfast can dig a 6 cm × 25–50 cm trench while maintaining productivity of 600 linear meters per day. In contrast, the Meteor can create a 1 cm × 10 cm trench at a higher productivity (2,400 linear meters per day) on a motorway (Marais 2012a and 2012b).

Figure 2-5: Meteor for MTT machines (Marais 2012a)

2.8. MTT Backfilling Materials

The functions of a backfilling material are to keep the conduit/cable in place and to provide mechanical and thermal protection to the cable against dynamic loading and high heat while the insulated trench resists water infiltration (ITU 2003; Duraline 2016). Since most of the MTT techniques use wet trenching, the mud-covered trench walls may cause poor adhesion between the backfilling materials and the existing pavement (ITU 2003). To provide a water-resistant restoration, good bonding materials include HMA, concrete, and epoxy mixtures (Duraline 2016). In addition, cold mix asphalt (CMA) can be an alternative solution in certain conditions.

2.8.1. Hot Mix Asphalt (HMA)

Today, HMA is being used to permanently repair most of the utility-cuts on pavement. HMA consists of aggregates, bituminous binder, and filler to provide a durable backfilling solution. However, in the case of a small utility-cut, compacting HMA has been found to be difficult, although an adequate compaction is extremely important for a quality restoration (Todres 1997). Additionally, it is very important to maintain the compaction temperature of HMA (Roberts et al., 1996) but difficult to maintain inside a small trench. It is therefore the placement, compaction equipment, and application temperature that determine the feasibility of HMA in small micro-trenches (Duraline 2016).

2.8.2. Hot Bitumen

Hot bitumen may provide a good bond between the backfilling material and the original pavement. Applying hot bitumen, however, requires special attention to be paid to the conduit/cable in order to protect it from any damages occurred by heat. Consequentially, a good bond material is always desirable, but the durability of restoration cannot be compromised (Duraline 2016).

2.8.3. Concrete/Grout

A quick setting, non-shrinkable, and flowable grout can be used to repair roadways or sidewalks and to backfill utility-cuts on roads. In a technical bulletin, Duraline reported that grout can be a filler material for MTT restoration (Duraline 2016). However, the grout should be selected and tested following the guidelines as shown in Table 2-1.

Table 2-1: List of tests on grout (after Duraline 2016)

ASTM Test Method	Properties
ASTM C-822	Material bonding and masonry standards
ASTM C-666	Rapid freeze/thaw characteristics
ASTM C-78	Flexural properties
ASTM C-109	Compressive strength
ASTM C-157	Length change factors
ASTM C-1107	Product flow rate
ASTM C-191	Setting time
CRD C-621 (U.S. Army Core of Engineers Standards)	Grout shrink factors

2.8.4. Cement-Treated Slurry

If a micro-trench reaches the subgrade layer of asphalt pavement, the stabilized-soil backfilling in the subgrade may result in an easy application and better restoration. For instance, a flowable cement-treated slurry usually mixed with soil has become an alternative for the utility-cut restoration in the subgrade layer so as to avoid compaction difficulties. The compressive strengths are usually expected to be no higher than 50 to 100 psi, enabling a subsequent re-excavation by the utility crews (Todres 1997).

2.8.5. Cold Mix Asphalt (CMA)

Some municipalities permit high performance CMA for permanently repairing keyhole openings and larger openings situated in less critical locations (Todres 1997). Applying CMA may result in difficulty during the compaction stage. The inadequate compaction of any CMA may yield a weak adhesiveness between the backfilled materials and the existing pavement (Duraline 2016). As well, most CMAs experience various failures during their service lives in the field (Anderson et al. 1988). Nonetheless, CMAs are easy to handle, highly workable, and suitable for MTT applications.

CMA is either an emulsified or cutback bitumen with reduced moisture susceptibility, which is commonly used for patching applications in flexible pavement during a winter or wet season when HMAs are not available (Prowell and Franklin 1996). The desirable properties of a CMA are stability, stickiness, durability, skid resistance, workability, storability, moisture resistance, and freeze-thaw resistance (Chatterjee et al. 2006). The following sections introduce the properties, problems, and previous studies of CMAs.

2.8.5.1. CMA Properties

CMAs consist of mineral aggregates, bituminous binders, and anti-stripping additives. Since a CMA is subjected to the same environmental and traffic-related stresses as a HMA, the quality of aggregates and the specification of a mixture should be designed and maintained carefully. The governing aggregate properties of a good patching mixture are grading, maximum size, angularity, shape, surface texture, and compatibility with the binder (Munyagi 2006).

A bituminous binder of CMA is capable of maintaining workability without heating the mixture, ensuring quick consistency is gained after compaction. It is either emulsified or cutback bitumen. The emulsified bitumen is dispersed in water in the form of discrete globules, which are held in suspension by electrostatic charges and stabilized by an emulsifier (Munyagi 2006). The cutback bitumen is dispersed in petroleum solvents (diluents) to reduce the viscosity and lower the application temperatures.

The main function of an additive is to increase the stripping resistance and to improve the workability of a cold mix when applied at low temperatures. An additive helps retain the coating of aggregates in stockpile and during handling and placing (Kandhal and Mellott 1981). Yet a

CMA experiences various problems at different stages of its life (i.e., stockpile, placing, compaction, and in-service).

2.8.5.2. CMA Problems and Their Causes

A cold mix may face various problems that may reflect in poor performances or premature failures in the field. Anderson et al. (1988) have enlisted these problems, and their causes are given in Table 2-2:

Table 2-2: Problems and probable causes in cold mix patching material (after Anderson et al. 1988)

Problem or Symptom of Failure	Probable Causes
In Stockpile	
Hard to work	Binder too soft; too many fines in aggregate; dirty aggregate; mix too coarse or too fine
Binder drains to bottom of pile	Binder too soft; stockpiled or mixed at high temperature
Loss of coating in stockpile	Inadequate coating during mixing; cold or wet aggregate
Lumps – premature hardening	Binder cured prematurely
Mix too stiff in cold weather	Binder too soft for climate; temperature susceptibility of binder too great; too many fines in aggregate, dirty aggregate; mix too coarse or fine
During Placement	
Too hard to shovel	Binder too stiff; too many fines; dirty aggregate; mix too coarse or fine
Softens excessively upon heating (when used with hot box)	Binder too soft
Hard to compact (appears “tender” during compaction)	Insufficient mix stability; too much binder; insufficient voids in mineral aggregate; poor aggregate interlock; binder too soft
Hard to compact (appears stiff during compaction)	Binder too stiff; excess fines; improper grading; harsh mix-aggregate surface texture or particle
In Service	
Pushing, Shoving	Poor compaction; binder too soft; too much binder; tack material contaminates mix; binder highly temperature susceptible, causing mix to soften in hot weather; in-service curing rate too slow; poor aggregate interlock; insufficient voids in mineral aggregate
Dishing	Poor compaction; mixture compacts under traffic

Ravelling	Poor compaction; binder too soft; poor cohesion in mix; poor aggregate interlock; moisture damage-stripping; absorption of binder by aggregate; excessive fines; dirty aggregate; aggregate grading too fine or too coarse
Freeze-thaw deterioration	Mix too permeable, poor cohesion in mix; moisture damage
Poor skid resistance	Excessive binder; aggregate not skid resistant; grading too dense
Shrinkage or lack of adhesion to side of hole	Poor adhesion; no tack used or mix not self-tacking; poor hole preparation
Note: In some instances, items appear as both symptoms and causes. It is difficult to separate the symptoms from the causes in some cases	

2.8.5.3. Previous CMA Studies

The Strategic Highway Research Program (SHRP) H-106 was the first major step to test CMAs at eight test sites across the United States and Canada, which included proprietary, state-specified, and local mixtures. The study concluded that local materials all had premature failures because of excessive ravelling, and the company-produced, experimental-repair materials had insignificant differences in patch survival. Ravelling is the loss of aggregates from the patch surface because of stripping, poor cohesion, excessive fine aggregates (passing No. 200 sieve), and poor aggregate interlock (Anderson et al. 1988). In addition to the field evaluations, the laboratory tests, including Marshall Stability, resilient modulus, and workability tests, helped in comparing these cold mixes, and the test results of the Texas site location are shown in Table 2-3. The compatibility between the aggregates and the binder was found necessary to avoid a premature failure (Wilson and Romine 1993).

Table 2-3: Test results of SHRP program (Texas) (Wilson and Romine 1993)

	Compaction Properties*			Marshall Stability (D 1559)*		Workability (PTI method)	Resilient Modulus (D 4123)*		
Mixtures	G_{mm} (D 2726)	G_{mb} (D 2041)	Air Voids (%)	Stability (N)	Flow (mm)	Blade Resistance (tons/ft2)	77°C, 0.33 Hz (ksi)	77°C, 0.35 Hz (ksi)	77°C, 1.00 Hz (ksi)
Perma-Patch	2.655	2.300	13.4%	20550	2.25	0.43	181.57	182.90	186.14
UPM	2.537	2.259	10.9%	22600	2.50	0.50	289.85	281.26	292.02
PennDOT 486	2.541	2.260	11.0%	11450	3.75	0.25	33.55	32.86	33.95
QPR 2000	2.609	2.243	13.8%	19600	3.25	0.25	160.44	159.82	159.86

* Samples were cured at 135°C overnight and compacted with 75 blows

Prowell and Franklin (1996) evaluated 13 proprietary cold mixes (PCMs) to identify the materials, which had similar properties to the materials already approved by the Virginia Department of Transportation (DOT). The materials were evaluated using field tests (in three test sections) and laboratory tests (e.g. coating, stripping, cohesion, adhesion, and workability tests). The laboratory tests concluded that two PCMs had reduced workability at low temperatures (-7°C and 4°C). However, all materials passed coating, cohesion, and workability tests as shown in Table 2-4. Survivability and durability were identified as the most important properties of a cold mix (Prowell and Franklin 1996).

Table 2-4: Test results of different mixtures (Prowell and Franklin 1996)

Mixtures	Coating Test AASHTO TP40-94 (% coated)	Stripping Test, AASHTO TP41-94 (% coated)	Workability (40°C) PTI method	Adhesion Test, Virginia DOT method (S)	Cohesion Test, AASHTO TP44-94
UPM	95-100	95-100	3.06	24	passed
QPR 2000	95-100	95-100	3.06	7	passed
Perma-Patch	95-100	95-100	2.38	20	passed
MacPatch CM-300	95-100	95-100	3.38	97	passed
Optimix Cold Mix	95-100	95-100	2.81	>120	passed
Tough Patch	95-100	95-100	3.31	>120	passed
Virginia Type P	95-100	95-100	3.00	19	passed

For the New Jersey DOT, Maher et al. (2001) evaluated five proprietary and one high quality permanent repair patching materials following the SHRP H-353 outline (a part of SHRP H-106 project). Besides the traditional Marshall Stability and resilient modulus tests, a rolling sieve test (at a temperature of -10°C and using 19.0 mm-sieve openings) was used to evaluate the cohesion, and a blade resistance test was applied to evaluate the workability of these mixes. The test results showed the discrete stability, strength, and cohesion values as illustrated in Table 2-5. There were no correlations between the indirect tensile strength (ITS) and the field performance and between the ITS and other laboratory test results (Maher et al. 2001).

Table 2-5: Test results of various mixes (Maher et al. 2001)

Mixtures	Marshall Stability (N)*	Marshall Flow (mm)*	ITS (kPa)*	Instant. Resilient Modulus (MPa)*	Total Resilient Modulus (MPa)*	Blade Resistance (N)	Rolling Sieve (% retained)
IAR	3,220.4	1.33	-	-	-	668.1	-
Performix	4,938.2	1.87	629.8	291.4	311.3	793.5	98.3
Perma-Patch	6,528.8	1.38	515.2	245.0	253.9	587.1	91.7
QPR 2000	5,472.8	1.40	510.6	216.5	282.8	378.1	93.6
SuitKote	4,752.2	1.42	418.9	286.6	241.5	858.1	95.6
UPM	4,952.4	1.20	613.4	248.8	282.8	608.5	21.8
WesPro	9,937.3	1.16	393.0	245.5	209.1	627.6	7.4

* Samples were cured at 135°C overnight and compacted with 75 blows

For the US Army Corps of Engineers, Shoenberger et al. (2005) evaluated 12 cold mixes (nine open-graded and three dense/well-graded) through field evaluation and laboratory tests, including workability, strength, and durability tests. The open-graded mixtures had higher workability than the dense/well-graded mixtures. Also, the dense-graded mixtures with a stiff binder mostly had higher Marshall Stability. Most of the materials showed good cohesive (following the AASHTO TP-44-94 standard) and some adhesive (following the Virginia DOT procedure) properties. They reported that the aggregate gradation probably has a greater effect on workability than the grade of the binder (Shoenberger et al. 2005).

On behalf of the Texas DOT, Chatterjee et al. (2006) evaluated the use and performance of patching maintenance mixtures (six containerized, three homemade, and one commercially produced stockpile mix) for cold and wet weather applications. A slump-based laboratory workability test was developed to measure the workability, and the wheel tracking and ITS tests measured the stability and strength of these mixes. They reported that homemade mixtures had durability, workability, and storage problems (Chatterjee et al. 2006).

For winter season pothole patching, Dong et al. (2014) evaluated three cold mixes (two bag mixes and one cold dump mix) and a HMA by using field survey (field test sections) and laboratory tests. The field survey results concluded that the severe weather (e.g. more freeze times), vehicle speed, and traffic level accelerated the patching failures. Furthermore, HMA was rated as the best material in the field, followed by two cold bag mixes and a cold dump. The laboratory tests measured the bonding, freeze-thaw resistance, and rutting potential of the patching materials through adhesiveness (following the Virginia DOT procedure), cohesion (using the AASTHO TP-44-94 standard), moisture susceptibility, and loaded wheel tests. The HMA showed the highest adhesiveness and strength. Two cold bag mixes had high adhesiveness and cohesion but low strength. The lone cold dump had low adhesiveness and cohesion (Dong et al. 2014).

Chapter 3. Field and Laboratory Investigations on Micro-Trenching Backfilling for Fiber-to-the-home Deployment

3.1. Introduction

Fiber optic (FO) network construction for high-speed broadband (more than 100 megabits per second) has been triggered by fiber-to-the-premises (FTTP) and fiber-to-the-home (FTTH) initiatives in many countries (Stirling Lloyd Polychem Ltd. 2011). Currently, several direct buried and utility sharing methods are available for building FO networks. The long-term performance of fiber networks is very important because of the significantly high FO deployment costs and the massive impact of broadband network failures on community and business (Crandall et al. 2009; Czernich et al. 2011; Holt and Jamison 2009). Direct buried methods include open-cut, which is not a reasonable and viable method due to the high costs of utility exploration and protection, surface restoration and landscaping, traffic control, and economic, environmental, and social impacts. Open-cut also impairs the integrity and longevity of pavement (Atalah et al. 2002). Mini-horizontal directional drilling, another direct buried method, requires utility inspection prior to the installation and digging entry and exit pits. Additionally, drilling in urban areas has high risks of hydraulic fracture, soil collapse, circulation loss (Osbak et al. 2012), and causing damage to other services, resulting in high deployment costs. To build FO networks using existing utility networks (e.g., sewer, water or gas lines), utility sharing methods require intensive collaboration between utility owners and telecom companies (Gokhale 2006). In addition, FO cable may be damaged by the maintenance, renovation, and replacement operations of the utility network. As a result, innovative, convenient, and reliable methods are increasing in popularity as promising options for FO deployment.

Micro-trenching Technology (MTT) is a new and alternative method for building FO networks. MTT places FO cable and sometimes conduit in a narrow trench, typically 2 cm wide and 12–30 cm deep, without disrupting or damaging existing underground infrastructures (DCMS 2011). MTT does not need the exploration and protection of underground services before and during construction. In busy downtown and community areas with minimal traffic detours and noise pollution and overall less impact during installations, MTT produces FO installations thirty times faster and five times less costly than traditional deployment methods (McDonnell 2009 and

Stahlbrand 2012). However, a MTT installation may encounter new challenges in cold climatic areas (Duraline 2016).

3.2. Background and Previous Studies

The MTT process consists of three major steps. The first step is the creation of the trench in pavement using appropriate trenching equipment. The second step is the installation of cable or conduit inside the trench, followed by the third step, which is trench backfilling.

Quality of backfilling plays an important role on the performance of MTT. It secures the cable in the trench bottom and provides a mechanical protection to the cable against traffic loads (ITU 2003). To ensure the trench backfilling as an integral part of the existing road, DCMS (2011) suggested the need for backfilling specifications that are agreed upon by road authorities and Internet service providers (ISPs). Reinstatement specifications could be different depending on pavement types.

In the case of MTT backfilling in flexible pavement, materials must be flexible, impermeable, flowable, stable, self-compacting, rapid hardening, and safe and simple to use. In rigid pavement, in addition to the required backfilling properties for flexible pavement, materials must be quick setting (Stirling Lloyd Polychem Ltd 2011). Hence, applying inappropriate backfilling may result in unsatisfactory performances of installations. Therefore, to evaluate the performance of installations, ISPs have tried various backfilling materials for MTT in different countries.

Among previous MTT projects, one project in the Caribbean in 2011 deployed FO cables (5.18 km) in 2.4 cm × 30.5 cm trenches on the asphalt pavement of the Cayman Islands. In regards to trench backfilling, Schultz (2011) reported that beach sand was applied as the bottom layer, and cold mix asphalt was filled and compacted as the final layer (Schultz 2011). However, the Cayman Islands have tropical marine climate with a wet season of warm, rainy summers and a dry season during the winter, completely different than the weather of Alberta. Hence, the backfilling performance will be significantly different compared with micro-trenches in cold climatic areas. In New Zealand, a pilot MTT project deploying FO cables (0.51 km) in 8 cm × 43 cm trenches on the asphalt pavement of Lower Hutt was completed in 2011. Trenches were filled using a specially designed mortar; after that, hot mix asphalt (HMA) was applied to seal the trench top (Chorus

2011). According to Chorus (2011), applying HMA required milling of a 40 cm wide and 2.5–3.0 cm deep ditch on the mortar-filled trench, and the milling operation resulted in pavement disturbance, dust and sound generation, and prolonged traffic detours. In addition, Lower Hutt has a humid climate with a relatively warm summer and mild winter that is quite different than the areas with freeze and thaw cycles. For cold climate MTT backfilling, Quanta Services proposed a non-shrink and re-excavatable grout for protecting FO cable from water ingression and traffic load damages (Trawick 2009). Since Trawick (2009) proposed trench-grouting in the asphalt layer of pavement, differential stiffness of grout and asphalt in the pavement may generate cracks and failures under dynamic traffic loadings and severe weather conditions. Additionally, when milling is done on the proposed MTT backfilling by Trawick (2009), road rehabilitations processes may damage the integrity of bonding between grout and conduit and between grout and original pavement. Therefore, any backfilling material needs to be tested for a certain regional application (Duraline 2016).

Since the MTT is a shallow installation, FO cables are most likely to be affected by freeze-thaw cycles and pavement rehabilitation processes. Freeze and thaw cycles may cause significant conduit movements, and as a result, the upward FO cable movement may substantially amplify the risk of damaging the fiber network. Moreover, a MTT backfilling may experience premature failures when trenches are restored with improper reinstatement methods and materials. Eventually, backfilling materials failures may damage the integrity and longevity of pavement (Arudi et al. 2000).

3.3. Objectives and Scope

The main objective of this research is to investigate the performance of different MTT methods in cold regions under freeze-thaw cycles and traffic loading. For this purpose, two different pilot installations were employed using vertical inlaid fiber (VIF) and surface micro cable inlay (SMCI) technologies and were monitored through several ground penetrating radar (GPR) inspections and visual observations. GPR inspections revealed significant FO cable movement, and visual observations concluded premature backfilling failures. Based on the evaluations, a modified backfilling method was proposed and evaluated using several laboratory tests.

3.4. MTT Pilot Installations

3.4.1. Details of Pilot Installations

In this study, two MTT installation methods, VIF and SMCI, were used. The installations were performed in a parking lot that belongs to a Telus operational building in Edmonton, Alberta. The first installation (VIF) was conducted on October 17, 2013, and the second one (SMCI) was performed on June 6, 2014.

3.4.1.1. VIF Technology

VIF technology deploys FO cable by using vertical deflecting conduit (VDC) in a narrow trench. VIF installation begins with marking the installation path, followed by cutting and cleaning the trench. Then, conduits fed with FO cable and wire tracer are inserted into the trench. In the final stage, trenches are backfilled with a layer of play sand and a layer of cold mix asphalt. A manually operated steel plate roller (100 lb weight) was used to compact the cold mix asphalt layer.

The solid line in Figure 3-1 depicts VIF technology layouts. Layout-1 shows a 30 m straight micro-trench located in a non-traffic zone. Layout-2 and Layout-3 show a 30 m straight and a 55 m loop micro-trench located in the direct path of traffic. As can be seen in Figure 3-2, in this technology, the depth of the trenches was greater than the existing asphalt layer thickness, and conduits were installed into the base layer.

Washed and flame-sterilized play sand was used in the bottom layer of VIF backfilling, as illustrated in Figure 3-2. Play sand is a fine-graded material, as can be seen from its grain size distribution, provided by the manufacturer, shown in Table 3-1.

CMA-1, an open-graded and proprietary cold mix, was applied and compacted as the final backfilling layer in VIF technology. It consists of polymer modified bitumen, additives and pressure-sensitive plastics. According to its specifications, CMA-1 does not require any mixing, heating or applying tack coat, and it can be applied in a temperature range of -28°C to 40°C. The mixtures' aggregate gradation is mentioned in Table 3-1.

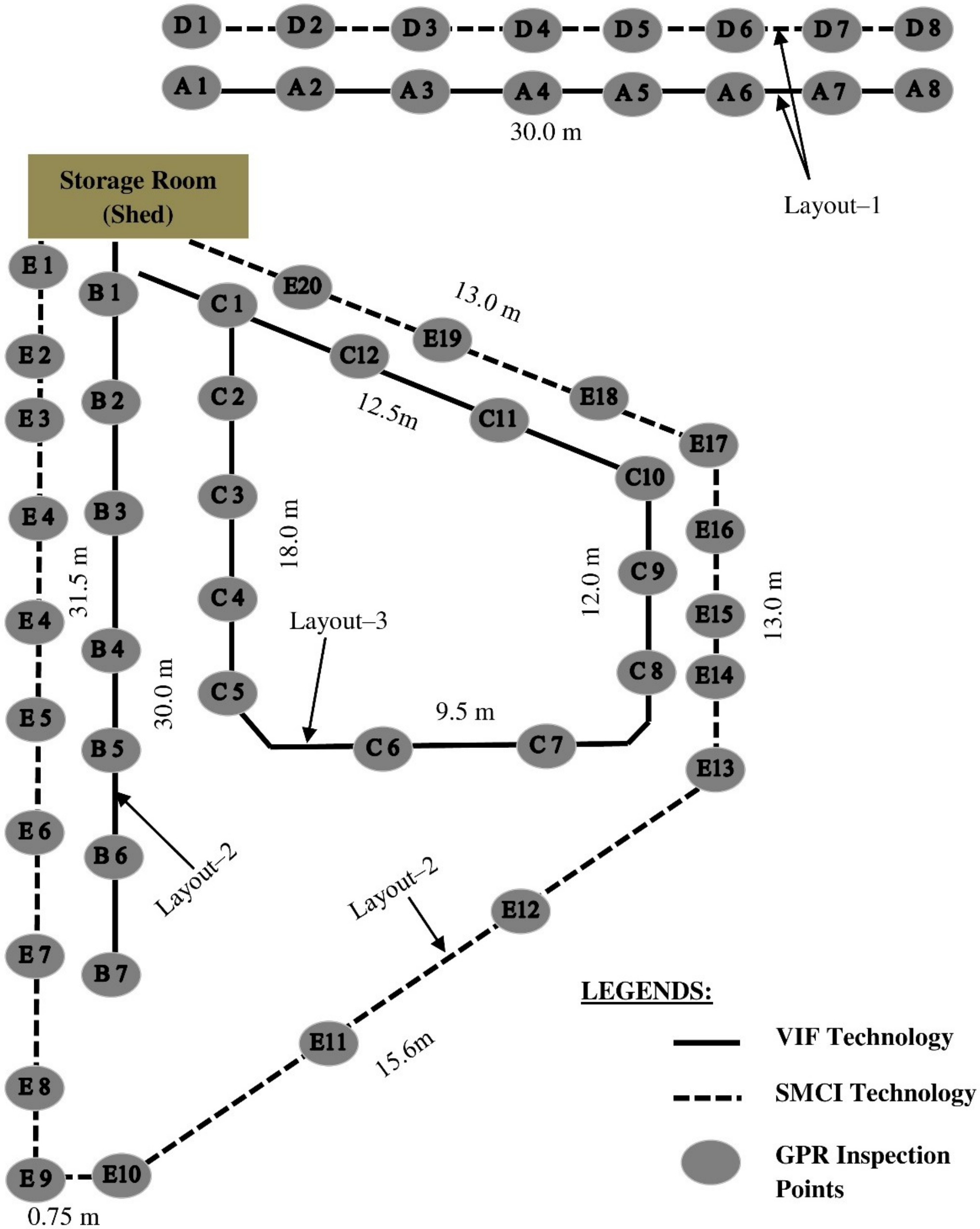


Figure 3-1: Layouts of MTT pilot installations (not to scale)

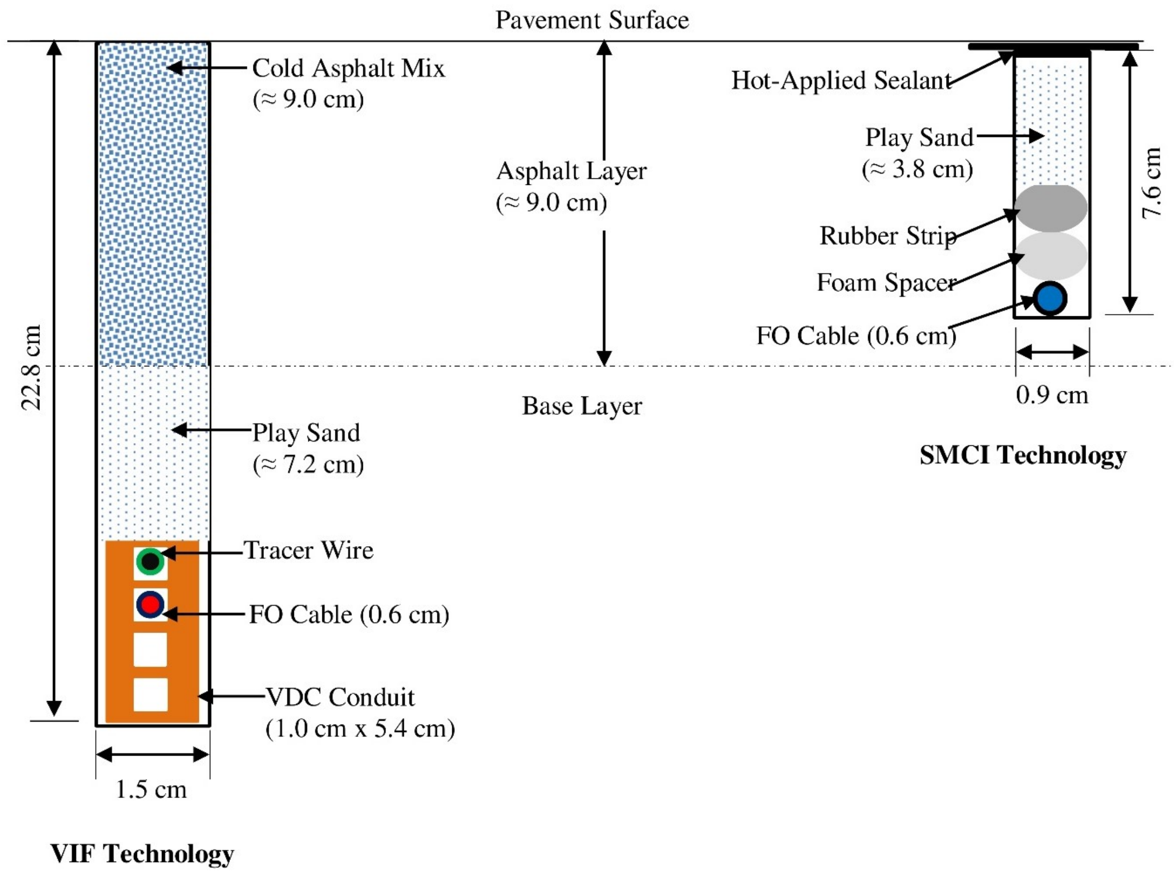


Figure 3-2: Cross-sections and backfilling details of MTT pilot installations (not to scale)

Table 3-1: Gradation of play sand and asphalt mixes

	Play Sand	CMA-1[a]	HMA
Sieve Size	% Passing	% Passing	% Passing
3/4”	-	-	100.0
1/2”	-	-	97.4
3/8”	-	100.0	-
#4	100.0	84.8	55.4
#8	100.0	21.8	37.4
#16	99.4	6.9	29.4
#30	94.2	4.0	24.7
#50	55.9	3.5	18.1
#100	11.0	3.3	11.4
#200	1.9	3.2	6.8

[a]Shoenberger et al. 2005.

3.4.1.2. SMCI Technology

SMCI technology deploys specially designed FO cable without using any conduit in a narrow trench at relatively shallower depths than VIF technology. SMCI and VIF technology have similar steps of marking, cutting, cleaning, conduit placement, and trench restoration. However, SMCI backfilling consists of play sand and bitumen sealant instead of cold mix used for VIF backfilling.

Layouts are shown in Figure 3-1 with a dashed line; a 30 m straight layout (Layout-1) located in a non-traffic zone and a 72 m loop layout (Layout-2) were in the direct path of traffic load. As Figure 3- 2 shows, the trenches are not deeper than the existing asphalt layer.

The backfilling materials consisted of foam spacer and rubber strips (for water resistance and heat insulation), play sand and sealant, sequentially, from the trench bottom as shown in Figure 3-2. A hot-applied bitumen sealant was applied on top of the sand layer to seal the trench. The sealant meets all the requirements of EN 14188-1:2004 Type N2 and ASTM D6690 (AASHTO M324), Type I. According to the sealant specifications, it can seal and fill cracks and joints of highways, streets, and airfields in both asphalt and Portland cement concrete pavements in moderate climates. Sealant properties are listed in Table 3-2.

Table 3-2: Properties of the sealant used in SMCI technology

Test Name	Test Method	ASTM D6690 (AASHTO M324) Type I Specification Limits
Cone penetration	ASTM D 5329	90 maximum
Softening point	ASTM D 36	80°C
Bond, -18°C, 50% ext.	ASTM D 5329	Pass 5 cycles
Asphalt compatibility	ASTM D 5329	Compatible
Minimum application temperature	NA	182°C
Maximum heating temperature	NA	193°C

Note: N/A = not applicable.

To evaluate and understand the long-term performance and functionality of MTTs while being exposed to freeze-thaw cycles and traffic loads, pilot installations were monitored using GPR and visual observation.

3.4.2. GPR Inspection Results

GPR, a quick and high-resolution technology for non-invasive investigation methods (Lester and Bernold 2007), locates the position of underground utilities, for instance, metallic pipes (Rashed and Morsy 2012), non-metallic pipes (Tong 1993), and power cables (Yelf 2007). GPR technology gives reliable results based on higher spatial resolution and continuous subsurface recording for civil engineering applications that are typically 0.3–2.0 m deep (Yelf 2007).

GPR technology was used to locate the position of FO cables in the trenches at different times in a year. These inspections reported the depth of FO cable relative to the pavement surface, and Fig. 1 shows the inspected points. The following sections discuss the results of both pilot installations.

3.4.2.1. VIF Technology

To easily locate the conduit position, VIF technology had tracer wire inside the conduit. GPR inspections were conducted on November 8, 2013; May 12, 2014; July 30, 2014; and May 4, 2015.

Figure 3-3 shows the conduit movements of VIF Layout-3 relative to the initial conduit location recorded immediately after the installation. Layout-3 was selected because it is located in a loop with bends and under traffic loading. As Figure 3-3 shows, conduit after six months of installation, including one winter, had a maximum downward movement of 5.9 cm and upward movement of 14.3 cm, meaning more than 50% loss of conduit backfilling coverage. One additional summer after the first inspection (nine months) resulted in a complete upward conduit movement with a maximum displacement of 14.3 cm relative to the initial position. After 18 months, including two winter seasons, conduit had become almost horizontal with a maximum upward displacement of 8.9 cm compared to the original location.

In VIF Layout-3, C6 and C7 had abrupt movements. To ensure accuracy of the GPR data in these locations, a site inspection was conducted, followed by the removal of backfilling materials and measurements of exact conduit depth. The results confirmed that the recorded depths of the GPR inspection were accurate. Since C6 and C7 are located near the 45° bends (intersection of two straight line segments), traffic loads, inadequate compaction of filling material, and adverse weather conditions could result in increased conduit movements in the loop layout compared to straight layouts.

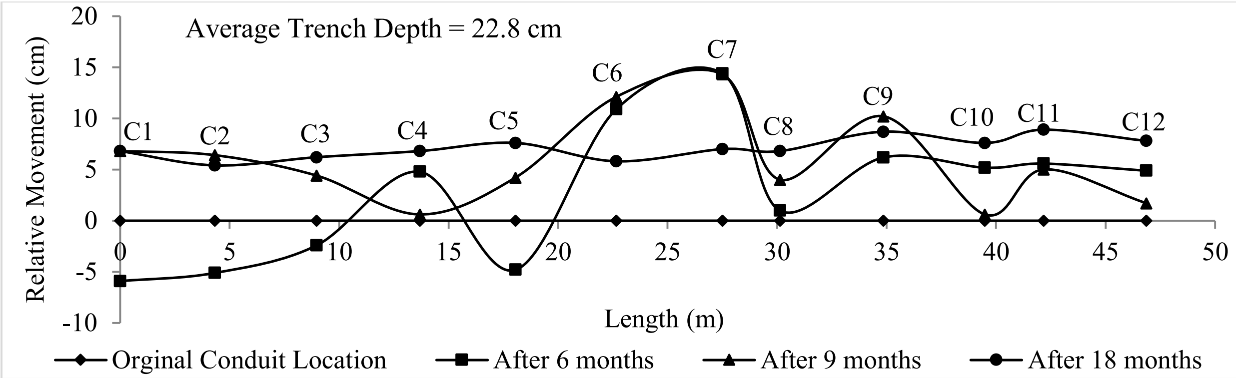


Figure 3-3: Conduit movement of VIF technology - Layout 3

3.4.2.2. SMCI Technology

SMCI technology has metal shell outside the FO cable to enable easy locating by GPR and to protect the cable from any damages. Inspections were conducted on July 30, 2014 and May 4, 2015.

Figure 3-4 shows the cable movements of SMCI Layout-2 (under traffic) with respect to the original cable locations recorded just after the installation. Nine months after the installation date, the cable had a maximum upward movement of 2.8 cm and downward movement of 2.6 cm, meaning the cable had lost one third of its cover. The highest displacements were found at the bends (e.g., 90° bend at E9), the intersections of two straight lines, which were increased by the traffic loads and adverse weather exposure.

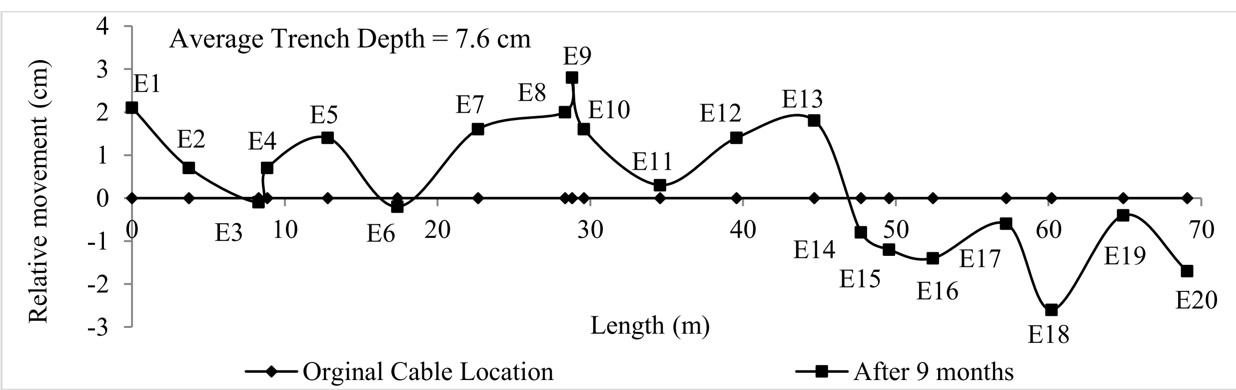


Figure 3-4: Conduit movement of SMCI technology - Layout 2

3.4.3. Site Inspection Results

Several visual inspections were also conducted to investigate the performance of trench backfilling. The results of field observation data of VIF and SMCI technologies are presented below:

3.4.3.1. VIF Technology

Visual observations of VIF technology are shown in Figure 3-5. As this figure shows, the observed failures are raveling, cracking, edge disintegration, and settlement. Raveling failure was severe in many locations and extended 1–2 cm deep, which could be due to several factors such as cold mix asphalt with poor cohesion, excessive fine aggregates (passing the No. 200 sieve), and poor aggregate interlock inside the material (Anderson et. al. 1988). Cracking failures were found in a few places; these cracks were typically 0.2–0.5 cm wide and opened the window for water ingress inside the trench. Since cracks usually happen due to poor cohesion inside the patching materials, cohesive materials are preferred for crack prevention. Edge disintegrations were also identified; these occur when there is a poor adhesion between the original pavement and patching material (Anderson et. al. 1988). Moreover, poor adhesion of a mixture may happen due to the mud-covered trench walls of MTT, which are a result of insufficient cleaning of the trench walls after saw cut. Since edge disintegration creates hollow slots between existing asphalt and trench backfill, water can easily penetrate into this gap, causing vertical displacement of FO cable during freeze and thaw cycles. Settlement of backfilling materials in some places was also prominent. The settlement may have been caused by inadequate compaction and unstable sand base. In other places, it was observed that cold mix asphalt material was completely washed out from the trench. This could be because of poor stability and high sensitivity of the selected cold mix asphalt to the freeze-thaw cycles.

Settlement and Material Washing Out | Raveling and Cracking | Edge Disintegration

Figure 3-5: Failures of VIF technology

3.4.3.2. SMCI Technology

SMCI visual inspection results are presented in Figure 3-6. Backfilled material in some areas experienced settlement, poor bonding, and pulling-out failures. Settlement was the dominant failure, which could be due to either choosing a soft sealant or further densification of the play sand under traffic load. Poor bonding was identified in a few places since sand and the existing asphalt edges made a weak bonding with the bitumen sealant, resulting in pulling out of the sealant. In these areas, water can easily penetrate into the trench, and freeze-thaw cycles will cause quick deterioration of this trench and backfilling. These failures can further be accelerated by traffic loads and severe weather conditions.

Settlement and Crack | Poor Bonding | Pulling Out

Figure 3-6: Failures of SMCI technology

3.5. Modified MTT Backfilling

The analysis of GPR monitoring results of MTT pilot installations concluded significant ups and downs of conduit over time. These vertical movements may eventually damage conduit and, consequently, FO cables and fiber networks. Visual observations showed that in both technologies, trench backfilling had several failures. This could be because of individual factors or a combination of several factors, for instance, execution method, improper backfilling material, insufficient compaction, traffic loads, and adverse weather conditions.

In VIF technology, poor durability, cohesion, adhesiveness, and stability of the cold mix asphalt accelerated the deterioration of trench reinstatement. Moreover, open-graded cold mix experienced settlement because of the sand layers underneath it and the difficulty in compaction in a narrow trench. On one hand, using open-graded cold mix asphalt enhances workability, resulting in reduced compaction effort and decreased backfilling time; on the other hand, it makes the cold-mix more permeable. Hence, exposing the trench to weather without being covered with a sealant does not offer a robust solution.

In SMCI technology, sealant makes weak bonding with play sand; therefore, it experiences pullover failure. Using soft sealant on a play sand surface resulted in settlement of the backfilled trench.

3.5.1. Proposed MTT Backfilling Section

To eliminate the aforementioned failures of pilot MTT, this study proposes a modified section (Figure 3-7). As shown in Figure 3-7, the proposal is to place conduit in the granular base under the asphalt layer, similar to the VIF method. One advantage of placing the conduit in the base layer is that it will protect the conduit from asphalt maintenance activities, such as milling and recycling. In order to prevent the conduit from moving vertically, the conduit will be stabilized with a cement grout in the base layer. The upper part of the trench in the asphalt layer will be filled with cold mix asphalt, and finally, the trench surface will be sealed with a sealant.

The following sections discuss the results of laboratory tests performed on the materials of the modified backfilling.

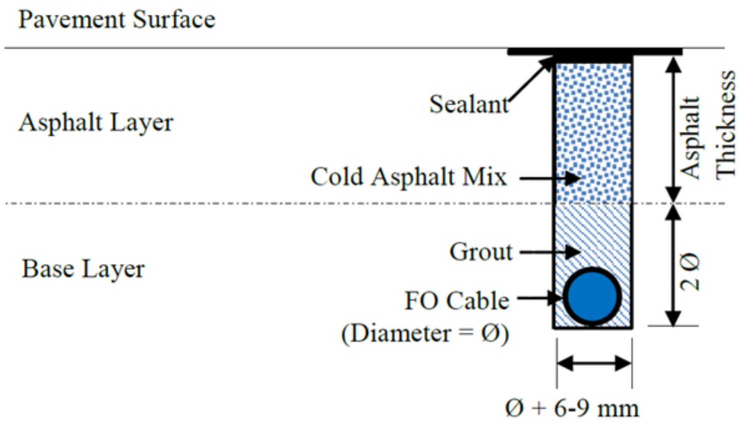


Figure 3-7: Cross-section of modified MTT backfilling

3.6. Conduit Stabilization in Base Layer

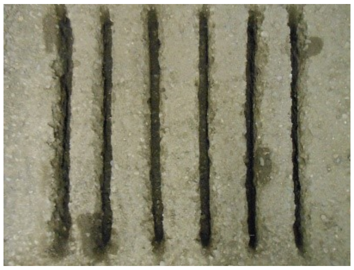
Grout was applied around the conduit to prevent movement (shown in Figure 3-7). Applied grout makes a strong bond around the conduit as well as with the base layer, stabilizing conduit inside the granular layer. A fast-setting, non-shrink cement grout is desirable for this purpose so as to shorten the execution time and prevent formation of shrinkage cracks in the upper backfilling layer. Grout water content was selected so that grout becomes flowable and self-compacted, enabling easy application inside the narrow trench.

Three different grout types were tested in the laboratory, and each grout requires only to be mixed with water before being poured into the trench. According to the manufacturer, grout-1 consists of cement and sand, and its working time and setting time are approximately 20 minutes and 20–45 minutes, respectively. Also, grout-2, consisting of coarser aggregates than grout-1 and grout-3, is comprised of blended hydraulic cement, graded-silica sand, and additives; its final setting time is 20 minutes. Grout-3 is a quick-setting, polymer-modified, and fine-graded mortar.

Laboratory tests on grouts, including coverage around the conduit, setting time, flowability, and compressive strength, are discussed in the upcoming sections.

3.6.1. Grout Coverage around the Conduit

To simulate conduit stabilization in the laboratory, a compacted slab from base material was prepared, as shown in Figure 3-8. The typical base material used for road construction in Edmonton with a maximum aggregate size of 19 mm was compacted with the optimum moisture content. Several trenches with a 2.5 cm width were excavated in the base slab for inserting the conduit (1.6 cm in diameter).



Trenches in the base slab

Grout-1 from left mixed at 25%, 37%, 31%, and 50% of water moisture

Figure 3-8: Grout for MTT conduit stabilization in the base layer

Grout coverage around the conduit depends on grout moisture content and types, conduit and trench dimensions, and conduit insertion-timing in the trench. Three different kinds of grouts (i.e., grout-1, grout-2, and grout-3) were mixed at a moisture content (fluidic consistency) as recommended by the manufacturer to enable pumping of grout into the trench with water contents of 25%, 14% and 18%, respectively. Higher water contents than the fluidic consistency may increase the shrinkage cracks and cause low strength, and lower water contents than recommended reduce the grout pumping capability. Hence, grout coverage may not be sufficient when the grout is not sufficiently flowable or excessively flowable. Figure 3-8 compares the coverage of conduit with grout-1 mixed at different water contents. As the figure shows, increasing water content more than the fluidic consistency resulted in less conduit coverage, and similar results were found for the other two grouts. This fluidic consistency can be selected as the optimum water content of grout.

Figure 3-9 compares conduit coverages for different grouts. Grout-1 and grout-3 created sufficient bonding around the conduit, and inserted conduit stayed at the grout bottom. However, in the case of grout-2, inserted conduit stayed at the grout surface because the grout had coarse aggregate; hence, this type of grout is not recommended for this purpose. Conduit is always expected to stay at the bottom of the trench, as it is in the case of grout-1 and grout-3.

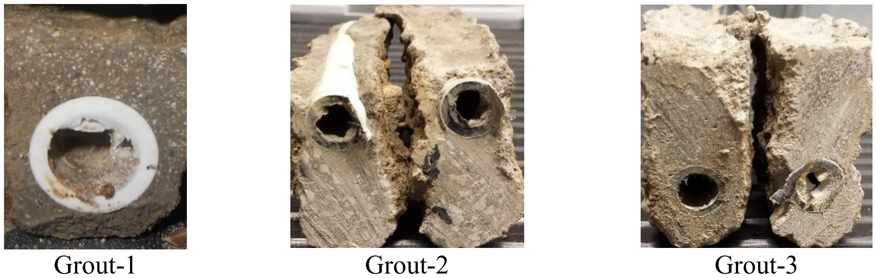


Figure 3-9: Grout coverage around the conduit

Conduit and trench dimensions should be designed in such a way that there are sufficient available spaces between conduit and trench walls in order to have uniform grout coverage around the conduit. Finally, conduit insertion time relative to the grout may make a difference in grout coverage. Grouts created better coverage when conduit was inserted after pouring the grout into the trench.

3.6.2. Grout Setting Time

Setting time is the required time for the grout to gain its sufficient strength, and it affects project duration and costs. It is a function of grout moisture content, water and air temperature, and trench dimensions.

A laboratory test was designed to incorporate the factors of setting time, especially the influence of air and water temperatures. For this purpose, several small trenches were prepared in the base soil and were filled with grouts (e.g., grout-1 and grout-3) that were mixed with water at fluidic consistency. Using an environmental chamber in the lab, air temperature was changed to investigate the effect of air temperature on grout setting time. Mixing water temperature was also increased from 22.1°C to 45.5°C since grout specifications recommended a high temperature of water for grout applications in cold weather. However, grout freezes at temperatures below 0°C.

Table 3-3 shows the result of setting time testing on grout-1 and grout-3. Setting time decreased as air and water temperature increased. For grout-1, setting time decreased as air and water temperature increased. As the figure shows, the setting time of this grout-3 is not significantly affected by water temperature. However, high air temperature reduced the setting time.

Table 3-3: Setting Time of Grout-1 and Grout-3

	Grout-1 (Water Content: 25%)				Grout-3 (Water Content: 18%)			
Setting Time (min)	4.5	20.0	*5.7*	*22.1*	0.0	10.1	*0.0*	*10.1*
Air Temperatures (^{O}C)	136	123	*115*	*22*	141	47	*125*	*43*

Note: For italic values, the mixing water temperature was 45.5^{O}C.

A comparison between the setting time of these two grouts shows that the setting time of grout-1 is more than grout-3 when the mixing water temperatures were low, and opposite results were found when mixing water temperatures were high.

3.6.3. Grout Compressive Strength

Compressive strength was performed according to ASTM C109/C109M–07 Standard. First, grout was mechanically mixed with optimum water contents, which was 25% for grout-1, 14% for grout-2, and 18% for grout-3, then poured in a 2 in-square mold. Next, demolded samples were transferred to a moist room to control the humidity and temperature. Finally, the samples were broken under compressive pressure, and the maximum load was used to calculate the compressive strength of the grouts.

Figure 3-12 shows the compressive strength test results. As expected, all grouts gained early strength, and they had much higher strength than the recommended strength. Despite that, grout-2 had coarse aggregates in the mixture, and it had the highest compressive strength at all curing ages. Considering the coarse gradation of grout-2, it may be a good option for backfilling the trenches in concrete pavements or sidewalks. Taking into account the price of grout-3 (five times more than grout-1), grout-1 was selected as the appropriate grout for conduit stabilization.

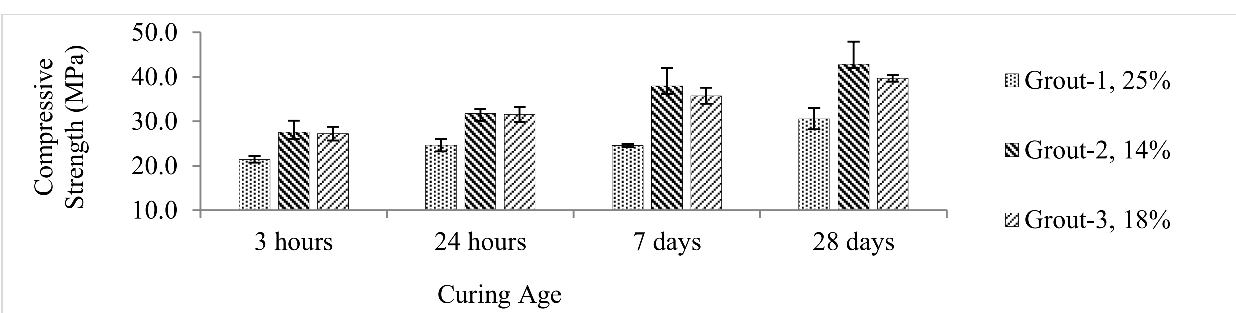


Figure 3-10: Grout compressive strength test results

3.6.4. Modified Compressive Strength Test on Frozen Samples

In cold regions like Alberta, MTT may need to be performed during winter seasons. When backfilling is applied below 0°C, grout freezes before completing hydration. After the temperature goes up, grout starts to thaw and reset, which is why freeze and thaw cycles may affect the compressive strength of grout. Therefore, a modification was added with the regular compression test for grout-1 to simulate the above condition in the lab.

After mixing, grout was poured into the molds and the molds were transferred to an environmental chamber with a temperature of -15°C. After the grout became completely frozen, the molds were taken out from the freezer and placed in a moist room. After 24 hours of thawing and setting in the moist room, the samples were demolded and restored in the same moist room. Finally, the samples were tested after one, seven, and 28 days of curing according to ASTM C109/C109M–07 Standard.

Figure 3-13 shows the effect of initial freezing on grout-1 at 25% of water content. Due to the initial freezing, compressive strength after one-day curing decreased from 25 MPa to 13 MPa. After seven days' curing, strength became almost similar to the samples that underwent no initial freezing. In contrast, compressive strength after full curing exceeded the strength of the non-frozen samples. Although micro-cracks were visible on the few frozen samples, they had no major influence on the strength.

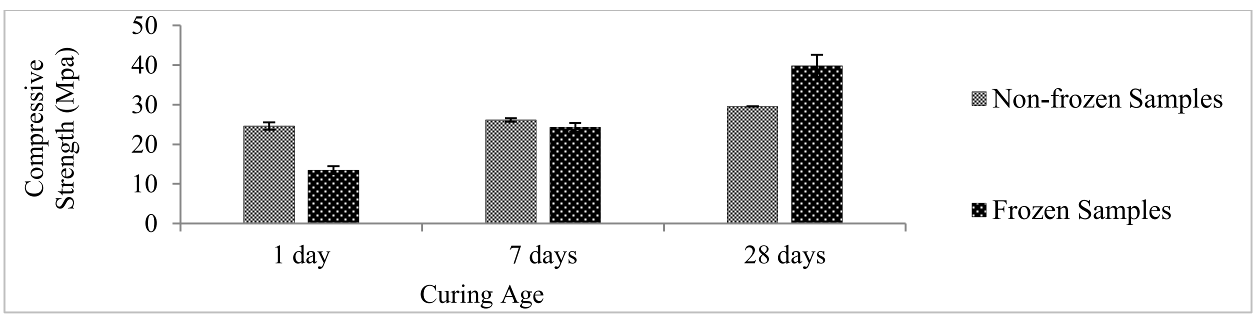


Figure 3-11: Effect of initial freezing on grout-1 at fluidic consistency (25% of water content)

3.7. Cold Mix Asphalt for Backfilling

To be consistent with the existing flexible pavement structure, cold mix asphalt was proposed to backfill the micro-trench, as shown in Figure 7. For MTT, applying HMA has some practical issues. Cold mix asphalt can be a suitable alternative as it is easy to handle, workable, flowable, and less sensitive to temperature variation during compaction.

From field monitoring results of VIF pilot installation, it was found that used CMA-1 experienced raveling, edge disintegration, and cracking failures. To minimize these failures, the mixture must have strong stability, durability, cohesion, adhesion, and freeze-thaw resistance (Chatterjee et al. 2006). To investigate the used CMA-1 properties, the following laboratory tests were conducted and compared to HMA.

3.7.1. Material Properties

The mixture properties of CMA-1 have already been discussed in Section 3.4.1.1, and aggregate gradations are shown in Table 3-1.

HMA aggregate gradation was similar to the City of Edmonton HMA that is usually used for patching applications, as shown in Table 3-1. To prepare the HMA samples, dry aggregates and 5% bituminous binder were mixed and compacted at 135°C.

3.7.2. Marshall Stability and Flow Test

Stability of a patching mixture is one of the most desirable properties for resisting deformation caused by traffic loading; lack of stability results in fatigue cracking and shoving and accelerates the failures of patches (Maher et al. 2001). Magnitude of stability depends on the aggregate type and grading and bitumen type, grade, and amount (ASTM D6927-06). In addition, adequate compaction increases the stability value by developing aggregate interlock (Maher et al. 2001). Flow index is mostly dependent on the aggregate properties (Roberts et al. 1996). A lower flow value indicates high internal friction of a mixture and thus a lower rate of permanent deformation in pavement (Maher et al. 2001).

Marshall Stability and flow test on CMA-1 was performed following the ASTM D6927-06 guideline, originally designed for HMA, with the addition of overnight curing at 135°C (Wilson and Romine 1993 and Maher et al. 2001) and 65°C (EBA Engineering Consultant Ltd. 2011) to add stability to the samples and to simulate the several months of field curing. Three samples were prepared for each curing temperature (135°C and 65°C). After curing, 1,200 g of materials for each sample were compacted using a Marshall Hammer in a 10 cm diameter Marshall Mold with 75 blows on each face. Three HMA samples were prepared and compacted at 135°C with similar compaction effort as CMA-1. When compacted materials reached room temperature, samples were extruded from the mold. Bulk specific gravity (G_{mb}) of the samples was calculated by weighing the samples in air, water, and saturated surface dry conditions. After that, samples were placed in a 60°C water bath for 30 minutes and then tested using a Marshall Apparatus. For each sample, a stability (lb) versus flow (0.01 inch) graph was obtained from the test. For calculating air voids of the samples, maximum theoretical specific gravity (G_{mm}) was determined for both materials.

3.7.2.1. Test Results

Typically, Marshall Stability is measured as the peak resistance load from the stability-flow graph. Marshall Flow is measured from the total elastic and plastic deformation of a bituminous mixture obtained during the Stability test (ASTM D6927-06).

Table 3-3 shows the test results of the modified Marshall Stability and flow test. CMA-1 samples cured at 60°C collapsed before testing. Additionally, Marshall Stability of the sample cured at 135°C is 5,400 N, which is quite less than HMA and could be the result of open gradation of the aggregates. Void contents of the cured samples was around 11%, so this mixture is permeable and cannot be a suitable alternative to HMA.

Table 3-4: Modified Marshall Stability and flow test results

Material	Stability (N)	Flow (mm)	G_{mb}	G_{mm}	Air Voids (%)
CMA-1	5,400	1.25	2.383	2.690	11.4%
HMA	17,350	2.75	2.355	2.430	3.1%

Note: Both Asphalt mixes had three samples and average values are presented here.

3.7.3. Indirect Tensile Strength (ITS) Test

An ITS test measures the moisture susceptibility of patching materials. Durability of patching mixtures highly depends on the freeze and thaw resistance of the material, especially in cold regions where freeze-thaw cycles exist (Dong et al. 2014).

In this study, an ITS test was conducted according to the AASHTO T 283-15 standard. Following this standard, the long-term stripping susceptibility of patching mixtures is determined by measuring the change in tensile strength of samples subjected to water saturation and accelerated water conditioning with a freeze-thaw cycle, then comparing them with similar properties of dry samples.

For sample preparation, CMA-1 was cured overnight at 135°C before being placed in a 10 cm diameter Marshall Mold and compacted with 75 blows of a standard Marshall Hammer on each face. The same HMA samples prepared for previous tests were used for ITS. Three sets of samples were prepared for each of the materials; the first set was tested for ITS value in dry conditions; the second set was saturated in water before testing for ITS; and the third set was tested after being conditioned with freeze and thaw cycles.

Dry samples were tested using a Universal Testing Machine (UTM) with a special loading frame with a displacement rate of 5 cm/min. A maximum compressive load of each sample was recorded from the test output. ITS was determined using Eq. (1). Notations are: S_t = tensile strength (kPa); P = maximum load (N); t = specimen thickness (mm); and D = specimen diameter (mm).

$$S_t = \frac{2000\,P}{\pi\,D\,t} \tag{1}$$

A second set of samples were placed in a 25°C water bath for 24 hours in order to maintain a 70–80% degree of saturation, as recommended by the standard. After saturation, each sample was tested using UTM with similar loading conditions in order to get the saturated ITS value. This saturated ITS value was used to determine the tensile strength ratio (TSR), which shows the effect of saturation on the patching materials.

The third set of samples was exposed to a freeze and thaw cycle. Samples were saturated in a 25°C water bath for 24 hours while maintaining the recommended 70–80% degree of saturation. After that, samples were wrapped with plastic bags and transferred to a -18°C freezer for a minimum of 16 hours. After freezing, samples were exposed to accelerated thawing in a 60°C water bath for 24 hours. Then, the water bath temperature was reduced from 60°C to 25°C within 15 minutes, and samples were left in the water bath for two hours. After a freeze-thaw cycle, samples were tested similarly, and the determined ITS value was used to calculate the TSR by using Eq. (2), which shows the freeze and thaw resistance of a material. Used notations are: S_1 = tensile strength of dry sample (kPa) and S_2 = tensile strength of saturated or conditioned sample (kPa)

$$\text{TSR} = \frac{S_2}{S_1} \tag{2}$$

3.7.3.1. Test Results

Moisture susceptibility of each material was measured by calculating the ITS value and TSR. Highly moisture-susceptible materials are subjected to raveling and stripping failures and particularly poor stability in deep patches (Esktakhri and Button 1995).

Table 3-4 represents the results of ITS testing. Cured and dry CMA-1 samples had around one third of the tensile strength of HMA. The TSR of CMA-1 in saturation shows that it was not susceptible to moisture, but after a freeze-thaw cycle, the TSR value decreased substantially. It is a clear indication that this mixture is highly sensitive to freeze-thaw cycles.

Table 3-5: ITS test results

	Average Indirect Tensile Strength (kPa)			Tensile Strength Ratio	
Material	Dry	Saturated	Freeze-Thaw	Saturation	Freeze-Thaw
CMA-1	522	494	290	0.95	0.56
HMA	1,634	1,733	1,335	1.06	0.82

Note: Average values are presented here.

3.7.4. Cohesion Test

Cohesion indicates the bonding strength inside of a patching material (Dong et al. 2014). It also shows the ability of compacted materials to remain together (Berlin and Hunt 2001) and the potential of raveling failure under traffic loading (Lavorato et al. 2013). Lack of cohesion causes raveling and missing patch distresses in repaired patches (Maher et al. 2001).

In this study, a cohesion test was performed following the rolling sieve tests (MTO LS-290 test) developed by the Ontario Ministry of Transportation (MOT) and revised by AASHTO TP–44–94. Materials were tested at temperatures of 4°C and 25°C. At 25°C, 1,000 g of loose material was placed in a 10 cm Marshall Mold and compacted using 15 blows of a standard Marshall Hammer on each side. After compaction, the sample was extruded and placed in a 30.5 cm diameter full height sieve with 2.54 cm square openings. The sieve was then covered with a lid and rolled back and forth on its side approximately 55 cm for 20 cycles. The recommended time is 20 seconds for 20 cycles. After rolling, the sieve was left in the same position for 10 seconds to allow the loose materials to separate. The remaining materials on the sieve were weighed in order to calculate the percentage of material remnants using Eq. (3). A few notations that must be introduced are W_i = Initial weight of the sample (g) and W_f = Materials retained on the sieve after the sample has been tested (g).

$$\text{Percent Material Remnants} = \frac{W_i - W_f}{W_i} \text{ x } 100 \quad (3)$$

For the other test temperature, loose materials were placed in the UTM environmental chamber at 4°C for 12 hours. After that, the samples were tested following a procedure similar to that of the 25°C temperature.

3.7.4.1. Test Results

Cohesion of a cold patch is measured by the percentage of materials retained on the sieve. A higher percentage of retained material indicates a more cohesive material. The minimum retained value is 60% according to the Ontario MOT (Dong et al. 2014).

Table 3-5 represents the cohesion test results. As can be seen, the remaining materials at both temperatures were very insignificant, meaning the CMA-1 had very poor cohesion.

Table 3-6: Cohesion and adhesiveness test results

	Cohesion Test		Adhesiveness Test	
	Average Remnant (%)			
Material	At 4°C	At 25°C	Adhesion Time (s)	Remnant (g)
CMA-1	0%	2%	1.08	8.93

Note: Average values are presented here.

3.7.5. Adhesiveness Test

Adhesiveness indicates the bonding strength between the original pavement and new patching materials, which is mainly dependent on mortar composition (asphalt binder and fines). Lack of adhesion causes edge disintegration and washing-out of patches (Dong et al. 2014).

An adhesiveness test was conducted according to the procedure used by the Virginia Department of Transportation (Dong et al. 2014). In order to prepare the sample, 500 g of loose cold mix was placed on top of a HMA sample (7.5 cm height) in a 10 cm diameter Marshall Mold and compacted at 25°C using 10 blows of a standard Marshall Hammer. After compaction, the sample was extruded from the mold. The extruded sample was held inverted until the compacted cold mix separated from the HMA surface. The time required for the separation of cold mix from the HMA surface was measured and recorded as the adhesion time. Also, the material attached to the HMA surface was measured; this is the remnant, which also shows adhesion property.

3.7.5.1. Test Results

Adhesiveness of a repaired patch is measured by the adhesion time and weight of remnant. For cold mixes, optimum adhesion time has been recommended as 5–30 seconds. Adhesion time lower than 5 seconds means excessive binder contents in a mixture; adhesion time higher than 30 seconds indicates insufficient binder content or a stiffer mix (Prowell and Franklin 1996).

Table 3-5 illustrates the adhesiveness test results. CMA-1 could be considered a poor adhesive material because the adhesion time was much lower than 5 seconds, and low amount of remnants indicated the same thing.

3.7.6. Discussion on Asphalt Test Results

The performed laboratory tests on CMA-1 and HMA showed that even after curing, cold mix asphalt had poor stability and very high air void content. Although it had low tensile strength, CMA-1 was insensitive to the moisture; however, susceptibility of this mix to freeze and thaw cycles was found to be too high. Also, it had poor cohesion and adhesiveness properties.

Comparing these results with the observed failures in the field shows that CMA may not be a suitable cold asphalt mixture to use for trench backfilling in cold regions subjected to freeze-thaw cycles, even if ideal compaction efforts are made. To enhance the backfilling quality, using a cold asphalt mixture with a better quality and stability may increase the trench durability.

3.8. Conclusions

Pilot installations have granted the opportunity to evaluate the performance of MTT in cold regions. This study, based on the field evaluation of different MTTs, has proposed a modified backfilled section. Laboratory tests helped to assess the feasibility and effectiveness of the proposed backfilling solution and materials. Key conclusions are listed below:

- VIF technology showed significant vertical movement of conduit in different seasons of the year. Cold mix used for backfilling (CMA-1) experienced raveling, cracking, edge disintegration, and settlement.
- SMCI technology, a relatively shallower installation, also faced substantial vertical movement of FO cable. Restoration materials showed settlement of backfilled surface, poor bonding between sealant and sand, and pulling out of sealant.
- A modified MTT backfilling section is proposed to avoid FO cable damage from road reconstruction and rehabilitation operations and to resist the vertical movement of conduit due to the freeze and thaw conditions in cold climate.
- Laboratory tests on the used cold mix asphalt in the field showed that the selected mixture was not suitable for cold regions subjected to freeze-thaw cycles. Improving mixture properties could be effective in increasing the trench durability in cold regions.

Chapter 4. Laboratory Investigations of Cold Mix Asphalt for Cold Region Applications

4.1. Introduction

4.1.1. Background

Cold mix asphalt (CMA), consisting of aggregate, bituminous binder (either emulsified or cutback), and additive, is mixed and applied at or near ambient temperature. It provides a rapid, low cost, and sustainable construction technology (Lesueur and Potti 2004). To maintain desired workability and compactability of CMA at low temperatures, bituminous binder is made less viscous either by emulsifying it in water with soap or by dissolving it in petroleum solvent prior to mixing with aggregates (Roberts et al. 1996). CMA is mostly preferable when hot mix asphalt (HMA) is not available during the winter or wet seasons (Wilson and Romine 1993).

Generally, CMA is applied in pothole repairs, which is one of the most performed maintenance activities in asphalt pavement due to cold winters and warm and wet springs contributing to frequent pavement failures (Estakhri and Button 1995). In addition to pothole patching, CMA can be an alternative material for utility-cut backfilling, road overlaying, edge repairing, and filling around manhole and water valves (EZ Street Asphalt 2014).

Today, utility-cut reinstatement has become a major problem in urban environments (Zeghal and El Hussein 1984), and its performance depends mainly on material, climate, traffic, and pavement conditions (SUDAS 2005). The difficult and time-consuming process of backfilling leads to poor performance (Maher 2013), especially for new construction techniques, which are less wide than traditional open-cut methods. CMA can be used as a restoral material for micro-trenching technology (MTT), which is an innovative method typically 2-cm wide and 12 to 30-cm deep (DCMS 2011) used for the installation of last-mile fiber optic (FO) networks (Griffin 2012 and ITU 2003).

Poor trench reinstatement contributes to premature failures within and around the utility-cut, resulting in increased maintenance costs (Peters 2002). Furthermore, CMA failures in pothole patching may result in a short-term substitution of HMA. Anderson et al. (1988), Prowell and

Franklin (1996) and Chatterjee et al. (2006) enlisted common cold mix distresses, for instance, bleeding, dishing, debonding (edge integration and missing patches), ravelling, pushing or shoving, and freeze-thaw resistance.

The causes of cold mix distresses can be a combination of several factors, such as weather and traffic conditions, application method and time, and mixture properties. For instance, severe weather (e.g., more freeze-thaw cycles) and high volume and speed of traffic accelerate the deterioration of patches (Dong et al. 2014). Mixture characteristics, while considering the same environmental- and traffic-related distresses for all CMA mixes, is a crucial and fundamental element in differentiating various mixtures and determining a CMA's service life and performance rating.

Mixture properties, such as aggregate gradation, binder property, and additive types, may significantly vary from one manufacturer's product to another, and they are important criteria for ensuring durable performance in CMA applications. Improper aggregate gradations result in high air void content and poor performance (Nicholls et al. 2014). For instance, open-graded aggregate results in poor durability and low freeze-thaw resistance, although it ensures good workability and rapid curing; conversely, too densely graded mixes can cause bleeding and poor workability; although, dense or well-graded mixes are more stable (Anderson et al. 1988 and Maher et al. 2001). In addition to aggregate gradation, the amount of fine particles in the mix determines the workability during placement and cohesion, adhesion, and performance under traffic loads (Kandhal and Mellott 1981; Roberts et al. 1996 and Chatterjee et al. 2006). Additionally, low binder content in a mix may cause poor cohesion, but high binder content may cause rutting, shoving, and bleeding failures. On one hand, too stiff binder may cause poor coating and reduced workability; on the other hand, too soft binder may cause rutting, shoving, stripping, and moisture damages (Anderson et al. 1988). Additives increase the stripping resistance and reduce the moisture susceptibility of the mixture (Prowell and Franklin 1996). To contrast different mixes' attributes, various laboratory tests for cold patching materials combined with field trials have become a vivid approach in the last few decades.

4.1.2. Previous Studies

Several studies have been reported on the evaluation of field performances of various cold mixes. The strategic highway research program (SHRP) H-106 was one of the first and most extensive studies on cold mixes for pavement maintenance using eight test sites across the United States and Canada (Evans et al. 1992; Wilson and Romine 1993, and Wilson 1998). The SHRP study concluded that all local materials had premature failures when applied to pothole patching because of excessive ravelling failures, and all experimental repair materials manufactured by different companies had insignificant differences in patch survival (Wilson and Romine 1993). Dong et al (2014) concluded from the field evaluations that severe weather (i.e., more freeze times), vehicle speed, and traffic level accelerated the failure of cold patches, and cold bags performed better than the cold dumps.

Along with field-testing, laboratory investigations have been an effective and widely practiced tool for evaluating CMA properties. The Virginia Department of Transportation (DOT) evaluated the performance of 13 proprietary cold-patching materials through coating, stripping, cohesion, adhesiveness, and workability tests (Prowell and Franklin 1996). Prowell and Franklin (1996) reported that all the materials passed coating, cohesion, and workability tests, and proprietary cold mixes performed better than the local materials. They identified survivability and durability as the most important properties of cold mixes. For the Texas DOT, Chatterjee et al. (2006) developed a slump-based laboratory workability test and used wheel tracking and ITS tests to measure the stability and strength of cold mixes. They reported that homemade mixtures had durability, workability, and storage problems. Dong et al. (2014) evaluated winter patching mixtures through cohesion, adhesion, moisture susceptibility, and accelerated loaded-wheel tests, and they drew conclusions that cold bag mixes had high adhesiveness and cohesion but low strength; however, cold dump had low adhesiveness and cohesion.

4.1.3. Objectives and Scopes

The main objective of this study is to evaluate the properties of 12 CMA materials that are being widely used across North America and to compare the results with a HMA material. For this purpose, a laboratory testing program was conducted to measure the CMA's properties, including stability, moisture susceptibility, freeze-thaw resistance, cohesion, and adhesion. This study will help in selecting a suitable cold mix based on test results and in predicting the CMA field performance when applied in cold areas.

4.2. Materials' Properties

Twelve different CMAs with different aggregate gradation types — open graded (OG) and dense or well graded (DG) — were selected from proprietary cold mix (PCM) and conventional cold mix (CCM). Moreover, mixes were categorized into four groups based on gradation and mixture types: OG-PCM, DG-PCM, OG-CCM, and DG-CCM. The following paragraphs summarize the mixture properties based on the information provided by the manufacturers.

CMA-1, OG-PCM, consists of aggregate, asphalt binder (cutback), polymer additive, and pressure-sensitive plastics. The mix does not require any mixing, heating or tack coating, and can be applied in a temperature range of -26°C to 40°C. The grade uses an average 0.25" aggregate; however, the complete gradation described in Table 4-1 was obtained from Shoenberger et al. (2005) since several attempts to get information from the manufacturer failed.

CMA-2 is a polymer-modified cold asphalt produced from the blending of mainland sand and gravel (85%), washed sand (15%), and polymerized cutback bitumen (4.7–0.9% for pre-coat and 3.8% for final blend). The type of aggregate and mixture is OG-PCM.

CMA-3 consists of crushed (minimum of 80%), washed or screened limestone or approved aggregates and modified cutback asphalt (4.5–6%) with special additives. For both dry and wet applications, coating and stripping tests (ASTM D–1664) resulted in 95% of coated aggregates. A workability test (MTO LS – 289) indicated that the mix is flexible and cohesive at -10°C and can be applied below zero degrees and in wet conditions. This is an OG-PCM asphalt.

CMA-4, OG-PCM, is composed of crushed mineral aggregates (100%) and modified cutback bitumen (4–6% of no volatile-organic-content liquid blend). It has the ability to coat wet aggregates (up to 4% moisture) without stripping, and the mixture has stripping resistance (more than 95% of coated aggregates).

CMA-5–7 have been designed for three seasonal grades (i.e., Summer (CMA-5), Fall and Spring (CMA-6), and Winter grade (CMA-7)) bituminous mixtures (PCM) for a temperature range of -26°C to 38°C. Each grade is produced from crushed aggregate (OG) and 5–6.5% of cutback bitumen binder. Aggregate coating test, ASTM D2489, concluded more than 95% of coated aggregates.

CMA-8 is a CCM asphalt consisting of mineral aggregate, filler, and emulsified bitumen. Aggregates retained on the 5.0-mm sieve is a minimum of 70% and has at least two crushed surfaces. The mix has a minimum emulsified bitumen of 7%, and the coating test, according to the ASTM D244 standard, reported 90% of coated aggregates.

CMA-9 is a high-float emulsion mixture. It is an OG-CCM, and the design procedure is similar to the cutback asphalt mixtures. If aggregates passing on the 80-mm sieve are more than 8% or have a Plasticity Index (PI) greater than 3, then these aggregates are not suitable for high-float emulsion. Bitumen contents are generally 5.5%, 6.5% and 7.5% for high-float emulsion mixtures while meeting the recommendations of blow/face = 75; Marshall Stability (N) at 25°C = 3000+; flow (mm) = 2–4; air voids (%) = 3–6.

CMA-10, a DG-CCM, is produced through conventional asphalt plants utilizing proprietary processes. DG aggregates are mixed with polymer-modified bitumen following a similar design formula as CMA-2.

CMA-11, DG-PCM, consists of sand, stone, cutback bitumen, and proprietary additives. Generally, 3–7% of PG64–22 bitumen is mixed with the aggregates.

CMA-12 consists of aggregate and 4.0–6.5% of cutback bitumen content. The mix has less than 10% stripping of aggregate surfaces, which Tex-530-C evaluated. This is also a DG-PCM asphalt.

In addition to testing the cold mixes, a HMA mixture, which had the same aggregate gradation of CMA-10 as shown in Table 4-1 with 5% of binder contents, was designed and tested. HMA samples were tested to have a benchmark for comparing with the cold mixes' test results. Table 4-1 presents aggregate gradations of cold mixes.

Table 4-1: Aggregate gradations of the mixes: (a) OGPCM materials (b) OGCCM, DGCCM, and DGPCM materials

(a)

CMA-1		CMA-2		CMA-3		CMA-4		CMA-5–7	
Sieve Size	% Passing	Sieve Size	% Passing	Sieve Size	% Passing	Sieve Size	% Passing	Sieve Size	% Passing
3/8”	100	3/8”	100	3/8”	100	3/8”	100	½”	-
#4	84.8	3/4”	95–100	#4	20–100	#4	20–85	3/8”	100
#8	21.8	1/2”	95–100	#8	1–60	#8	2–30	#4	85–100
#16	6.9	#4	44–52	#16	0–50	#16	0–10	#8	10–40
#30	4.0	#8	9–17	#50	0–20	#50	0–6	#16	0–10
#50	3.5	#16	4–12	#200	0–5	#200	0–2	#50	0–5
#100	3.3	#50	1–9						
#200	3.2	#100	0–6						
(Shoenberger et al. 2005)		#200	0–6						
		Pan	05–3.5						

(b)

CMA-8		CMA-10		CMA-11		CMA-12	
Sieve Size	% Passing	Sieve Size	% Passing	Sieve Size	% Passing	Sieve Size	% Passing
½”	100	1/2”	95–100	3/8”	100	1/2”	100
#4	60–80	3/8”	95–100	#4	20–85	3/8”	95–100
#100	9–14	#4	68–78	#8	2–30	1/4”	75–100
#200	4–7	#8	20–30	#16	0–10	#10	8–30
		#16	11–19	#50	0–6	#40	3–15
		#50	7–15	#200	0–2	#80	2–10
		#100	5–11	Pan	0		
		#200	2–8				
		Pan	2.4–5.4				

4.3. Laboratory Investigations of Cold Mix Properties

Marshall Stability and ITS tests were originally designed for HMA. Incorporating some modifications as proposed in previous studies, these tests can be applied for evaluating CMA properties in the laboratory. In addition to the Marshall Stability and ITS tests, adhesiveness and cohesion tests were conducted, including proprietary and conventional mixes. Among four tests, freeze-thaw resistance was evaluated as one of the most important parameters since patching materials experience premature failures when exposed to severe weather during winter in cold regions.

4.3.1. Modified Marshall Stability and Flow Test

Because poor stability results in fatigue cracking and shoving failures and escalates patch deteriorations, stability is one of the most desirable properties of a patching mixture against deformation caused by dynamic traffic loading (Maher et al. 2001). The stability of any mixture depends on the type and grading of aggregate and the type, grade and amount of bituminous binder (ASTM D6927-06). Since stability is a function of compaction effort, proper compaction enhances aggregate interlock and results in increased patch stability (Maher et al. 2001). In contrary to stability, flow value is typically dependent on the aggregate properties (Roberts et al. 1996), and a higher flow index indicates low internal friction of a mixture and thus a higher rate of permanent deformation in pavement (Maher et al. 2001).

The Marshall Stability and flow test was conducted according to the ASTM D6927-06 standard with an inclusion of overnight curing of materials at 135°C and 65°C proposed by Wilson and Romine (1993) and EBA Engineering Consultant Ltd. (2011), respectively. These curing processes helped to add stability to the samples and to simulate the field conditions after several weeks of patching. Three samples were prepared for each curing temperature. After curing, Marshall samples were prepared by using 75 blows of a standard Marshall Hammer on both faces. The applied loading rate on the samples was 51.0 mm/min after conditioning at 60°C in a water bath (Roberts et al. 1996). A stability (lb) vs flow (0.01 inch) graph was obtained for each tested sample.

4.3.2. ITS Test

An ITS test measures the moisture and freeze-thaw susceptibility of asphalt mixes. Freeze and thaw resistance of a material mostly affects the durability of patching, especially in cold regions where pothole generation and repaired-patch failure are caused by freeze-thaw cycles (Dong et al. 2014).

In this study, an ITS test was performed following the AASHTO T 283-15 guideline. Following the standard, the long-term stripping potential of a patching mixture is determined by measuring the change in ITS of samples subjected to water saturation and accelerated water conditioning with a freeze-thaw cycle, then compared with the same properties of dry samples.

At the beginning of sample preparation, materials were cured overnight at 135°C (Wilson and Romine 1993) and compacted with 75 blows on each side. Three sets of samples were prepared for each material; each set consisted of three samples. The first set was tested for ITS value in dry conditions; the second set was saturated in water before testing for ITS; the third set was tested after conditioning with a freeze and thaw cycle.

For the first set, dry samples were placed inside a special loading frame in the Universal Testing Machine (UTM) and tested with a constant displacement rate of 50 mm/minute. Out of the many test outputs, the maximum load of each sample was identified, and the ITS value was determined using Eq. (1).

$$S_t = \frac{2000\,P}{\pi\,D\,t} \tag{1}$$

Where,

S_t = tensile strength in kPa

P = maximum load in N

t = specimen thickness in mm

D = specimen diameter in mm

The second set of samples was placed in a water bath at 25°C for 24 hours and maintained a 70–80% degree of saturation as recommended by the AASHTO standard. After saturating the samples, a UTM with similar loading conditions was used in order to get the saturated ITS value. The saturated ITS value provides the tensile strength ratio (TSR), which indicates the effect of saturation on the patching materials. TSR was calculated using Eq. (2).

The final set of samples was exposed to a freeze and thaw cycle. Before applying the freeze and thaw cycle, the samples went through a saturation process similar to the second set. Then, samples were wrapped with plastic bags and transferred to a freezer at -18°C for a minimum of 16 hours.

After freezing, samples were exposed to accelerated thawing in a water bath at 60°C for 24 hours. The water bath temperature was reduced from 60°C to 25°C within 15 minutes, and samples were left in the same water bath for another two hours. Samples were tested following a procedure similar to previous sets, and the determined ITS value was used to calculate the TSR by using Eq. (2), which shows the freeze and thaw resistance of a patching material. According to the AASHTO T 283-14 standard, the minimum TSR value for asphalt mixes should be 0.8.

$$\text{TSR} = \frac{S_2}{S_1} \tag{2}$$

Where,

S_1 = tensile strength of dry sample in kPa

S_2 = tensile strength of saturated or freeze-thaw sample in kPa

Figure 4-1 shows failure types of ITS samples.

Cracked Sample

Separated Sample

Figure 4-1: Types of sample failures

4.3.3. Cohesion Test

Cohesion is an indicator of the bonding strength inside a patching material (Dong et al. 2014). It is the ability of compacted materials to remain together (Berlin and Hunt 2001) and the potential of ravelling failure under traffic wheels (Lavorato et al. 2013). Poor cohesion causes ravelling and missing patch distresses in repaired patches (Maher et al. 2001).

The cohesion test was conducted according to the rolling sieve test, which is developed by the Ontario Ministry of Transportation (MOT), and later AASHTO TP–44–94 revised the procedure as a standard. Materials were tested at two temperatures: 4°C and 25°C (Dong et al. 2014). For 25°C, 1,000 g of loose materials for each sample were placed in a 100-mm diameter Marshall Mold and compacted with 15 blows of a standard Marshall Hammer on both faces. After compaction, samples were extruded and placed in a 30.5-mm diameter full-height sieve with 25.4-mm square openings. The sieve containing a sample was covered with a lid and rolled back and forth on its side approximately 550 mm for 20 cycles. The recommended duration is approximately 20 seconds for 20 cycles. After rolling, the sieve was left in the same position for 10 seconds to allow the loose materials to separate. The remaining materials on the sieve were weighed in order to calculate the percentage of material retained using Eq. (3).

$$\text{Percent Material Remnants} = \frac{W_i - W_f}{W_i} \text{ x } 100 \tag{3}$$

Where,

W_i = Initial weight of the sample in g

W_f = Materials retained on the sieve after the sample being tested in g

For the other test temperature, loose materials were placed in the UTM environmental chamber at 4°C for 12 hours before compacting the samples. After that, the samples were tested following a similar procedure at a temperature of 25°C. Figure 4-2 shows the test procedure. The minimum retained value is 60% according to the Ontario MOT (Dong et al. 2014).

Sample weighing | Sample extruding | Sieve rolling | Remnant weighing

Figure 4-2: Procedure of the rolling sieve test

4.3.4. Adhesiveness Test

Adhesiveness is an indicator of the bonding strength between the original pavement and new patching materials, which is mainly dependent on mortar composition (i.e., asphalt binder and fines). Poor adhesion of a material causes edge disintegration and washing-out (Dong et al. 2014).

In this study, the adhesiveness test was conducted according to the Virginia DOT procedure (Dong et al. 2014). For preparing samples, 500 g of loose cold mix was placed on top of a HMA sample (75 mm-height) in a 100-mm diameter Marshall Mold and compacted with 10 blows of a standard Marshall Hammer. The sample was extruded from the mold. The extruded sample was held inverted until the compacted cold mix separated from the HMA surface. The time required for the separation of cold mix from the HMA surface was measured as the adhesion time. Also, materials attached on the HMA surface were measured as the remnant, which also shows the adhesion property of a material. For cold mixes, optimum adhesion time has been recommended as 5 to 30 seconds. Adhesion time lower than 5 seconds means excessive binder contents in a mixture and higher than 30 seconds indicates insufficient binder content or a stiffer mix (Prowell and Franklin 1996). Figure 4-3 shows the test procedure.

Compaction Cold mix on HMA Measure time Weight remnants

Figure 4-3: Procedure of the adhesiveness test

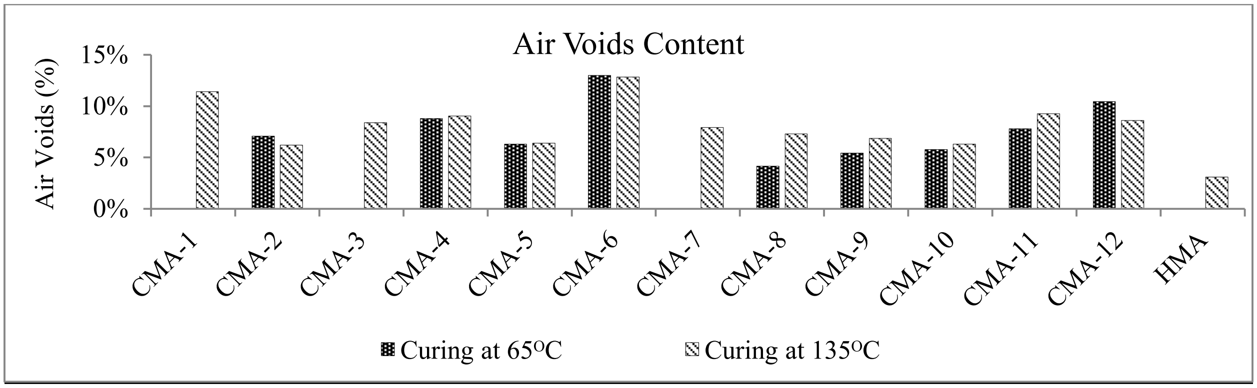
4.4. Discussion on Laboratory Tests Results

4.4.1. Modified Marshall Stability and Flow Test

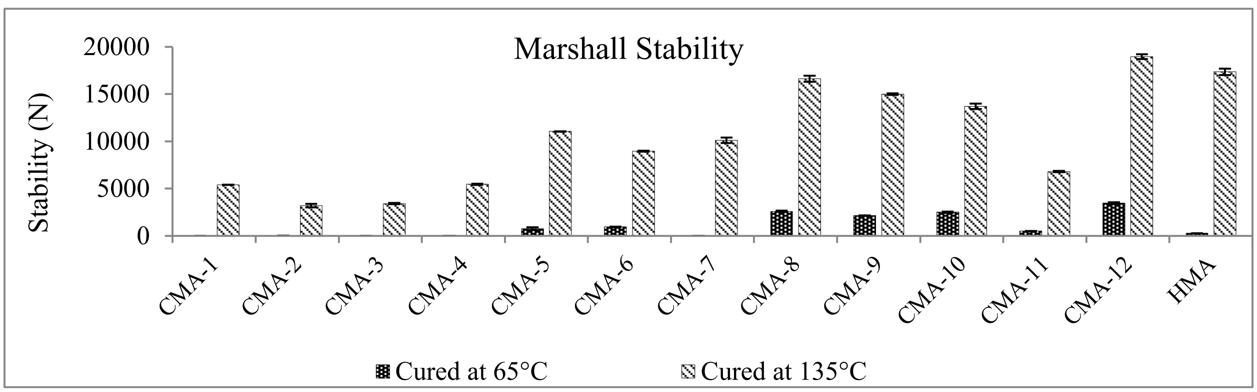
Generally, Marshall Stability is derived from the stability vs flow graph as the peak resistance load (ASTM D6927-06). A higher stability value indicates better cohesion of a material, and patching materials would perform better under traffic load (Maher et al. 2001). Conversely, Marshall Flow is the total elastic and plastic deformation measured from the stability-flow graph of a bituminous mixture (ASTM D6927-06). A higher flow value indicates low internal friction of a material as a result of higher deformation of the repaired patch (Maher et al. 2001). The stability to flow ratio is known as Marshall Quotient (MQ), and it indicates the resistance to shear stress, mix stiffness, and rutting of the bituminous mixtures. A high MQ represents high stiffness or low workability and high strength to cracking of a mixture (Hattatoglu and Hinislioglu 2015).

Figure 4-4 shows the results of modified Marshall Stability and flow test. Only, CMA-1 and CMA-6 had higher air voids than the recommended void-content limits for cold mixes (5–10%). As expected, samples cured at a higher temperature had higher stability than samples cured at a lower temperature. This might be because of relatively lower binder viscosity and lower binder stiffness. Despite curing at 65°C for 14–18 hours, samples of CMA-1, CMA-2, CMA-3 CMA-4, and CMA-

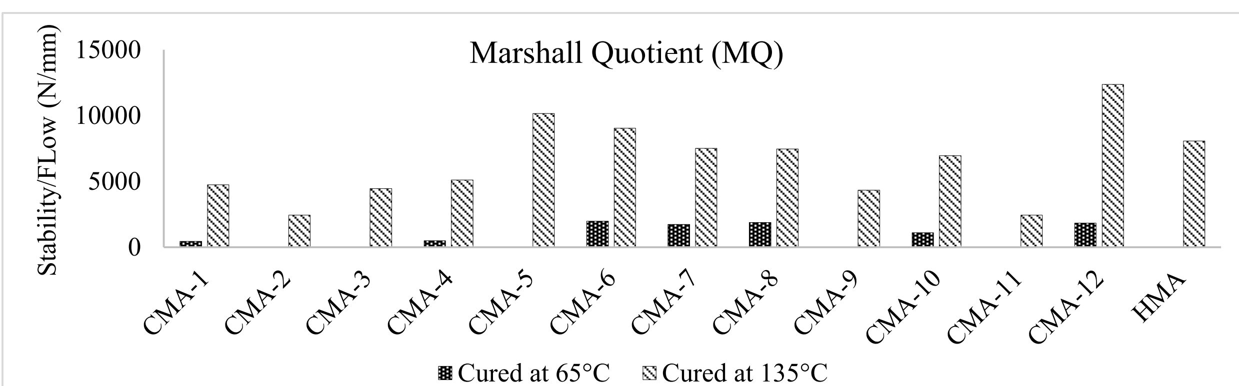
7 collapsed prior to the test. However, at higher curing temperatures, only CMA-5–7 from OGPCM, all DGPCMs, all CCMs, and HMA had high stability, but the rest of the OGPCM had low stability indicated by high air voids. CMA-5 and CMA-12 had very high MQ, indicating very high stiffness and low workability of these mixes, as this was also observed in the lab.



(a)



(b)



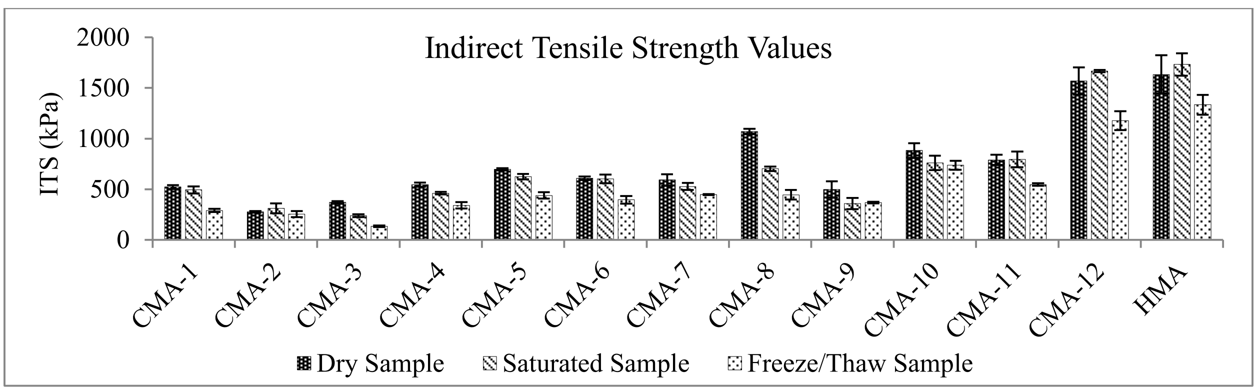
(c)

Figure 4-4: Results of modified Marshall Stability and flow test

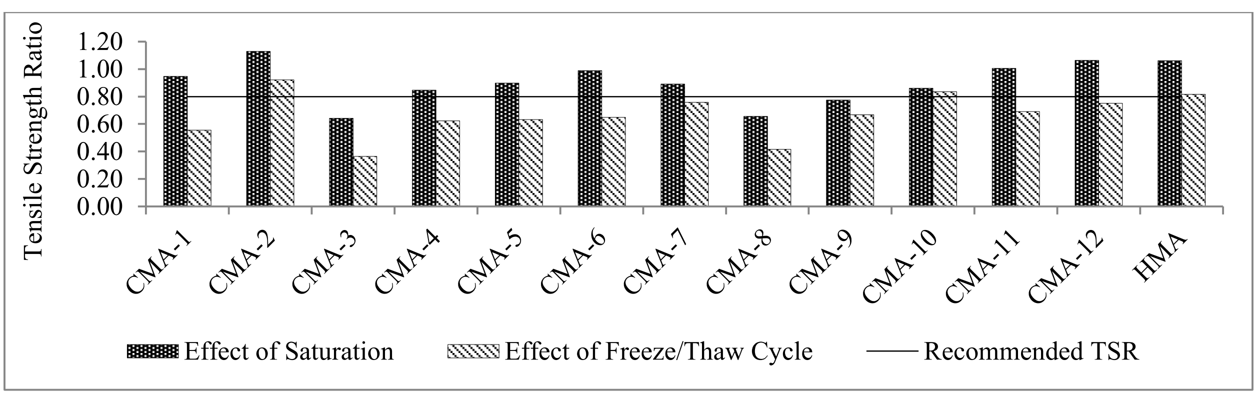
4.4.2. ITS Test

Moisture susceptibility of patching materials is measured based on the ITS and TSR parameters. Highly moisture-susceptible materials are subjected to ravelling and stripping failures and have poor stability, especially in deep patches (Estakhri and Button 1995).

Figure 5-5 represents the ITS test results. HMA had the highest tensile strength in dry conditions, followed by dense-graded and open-graded mixes with the exception of CMA-8. CMA binders had still lower viscosity than the traditional HMA, even after curing at 135°C for 14–18 hours; hence, their tensile strength was lower. After saturating the samples, TSR indicates that none of the mixes, except CMA-3, CMA-8, and CMA-9, are susceptible to moisture conditions, and the TSRs are comparable to HMA. After subjecting the samples to a freeze and thaw cycle, only CMA-2 and CMA-10, had comparable moisture susceptibility to HMA. However, TSR values of CMA-7 and MCA-12 mixes were also very close to the required specification (TSR = 80%).



(a)



(b)

Figure 4-5: Results of ITS test

4.4.3. Cohesion Test

Figure 4-6 shows the results of the cohesion test. As predicted, cold mixes were more cohesive at a higher temperature than at a lower temperature. Among DGPCM and CCM mixes, CMA-10, CMA-11, and CMA-12 were highly cohesive at both test temperatures; however, CMA-8 was found cohesive at 25°C, but significantly less cohesive at 4°C. Most of the OGPCM mixes were less cohesive because of low bitumen viscosity with the exception of CMA-5 and CMA-6 mixes at both testing temperatures.

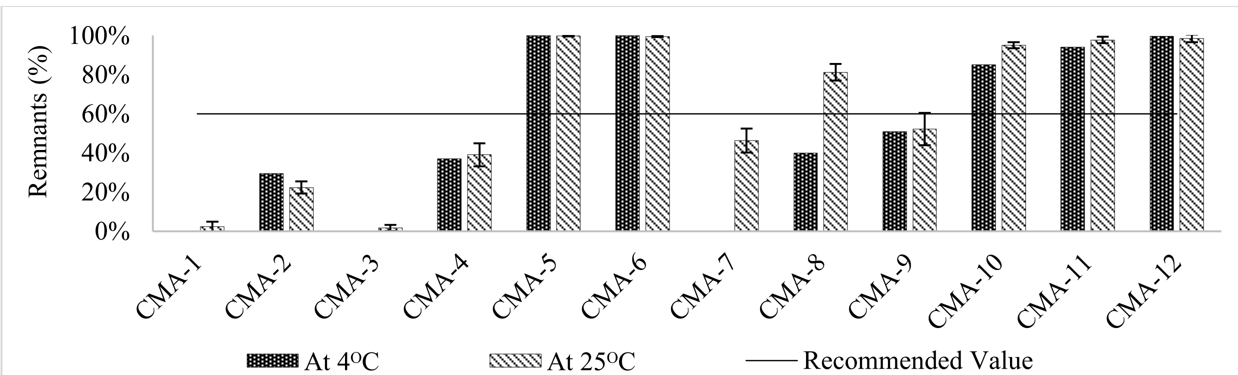


Figure 4-6: Results of cohesion (rolling sieve) test

4.4.4. Adhesiveness Test

Figure 4-7 shows the results of the adhesiveness test. CMA-5 and CMA-12 had adhesion times longer than 30 seconds, which could be the result of insufficient or stiffer binder. CMA-6 and CMA-11 had the recommended adhesion time, indicating sufficient bonding strength of patching materials with existing pavement. However, the rest of the mixes had adhesion time much lower than the recommended. Likewise, remnant is also an indicator of the adhesiveness of a patching material, and it usually follows the same ranking as adhesion time.

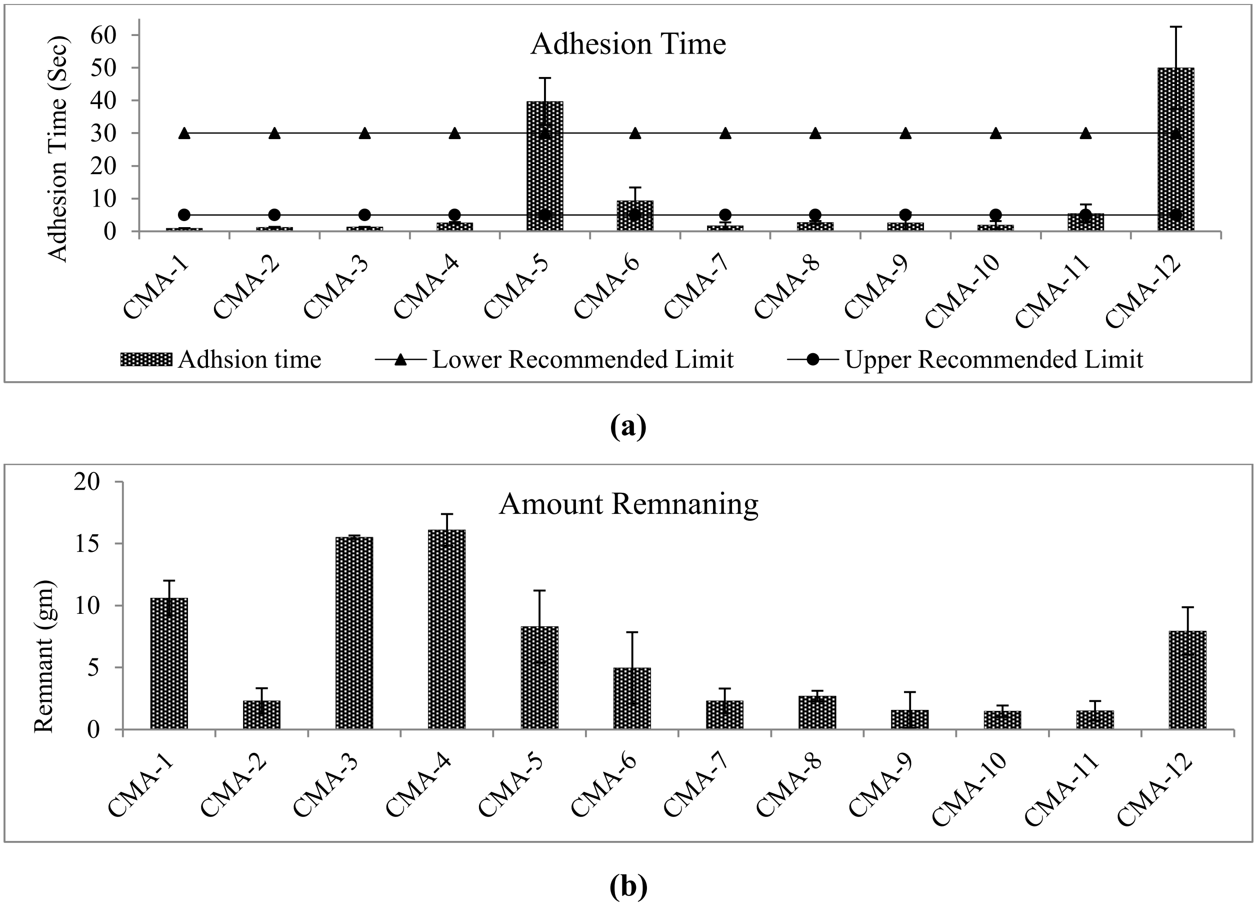


Figure 4-7: Results of adhesiveness test

4.5. Conclusions and Future Research

Table 4-2 summarizes the laboratory tests results, including the recommended limits of all test parameters. As can be seen in Table 4-2, none of the cold asphalt mixes satisfied all the required specifications. Among PCM, OGPCMs had very poor properties with the exception of CMA-6, which only failed in freeze-thaw conditions. From the group of DGPCM, CMA-10 had acceptable properties, but it was susceptible to freeze and thaw cycles.

Alternatively, among the CCMs (OGCCM and DGCCM), only CMA-10 had superior material properties despite its poor adhesiveness. Hence, careful consideration should be taken in selecting a suitable CMA, accounting for application type and climatic conditions. For example, CMA-12 may be an appropriate option for pothole patching in conjunction to using a tack coat layer, but its workability is not suitable for using it in micro-trenches of MTT. CMA-6 and CMA-11 mixes seem to be appropriate mixtures for both pothole patching and utility-cut backfilling, but not for the cold regions that are subjected to freeze and thaw cycles. In the case of using these mixtures in utility-cut (e.g., MTT backfilling) in cold regions, using a sealant on top is highly recommended. Whereas CMA-10 is not a good solution of MTT backfilling due to its coarser gradation and poor adhesiveness; however, it can be a good solution for pothole patching in cold regions.

Table 4-2: Summary of the test results

Laboratory Test Name	Tested Parameters	CMA-1[a]	CMA-2[a]	CMA-3[a]	CMA-4[a]	CMA-5[a]	***CMA-6[a]***	CMA-7[a]	CMA-8[b]	CMA-9[b]	***CMA-10[c]***	***CMA-11[d]***	CMA-12[d]	Parameter's Recommended values
Marshall Stability	Stability (N)[1]	**5,400**	**3,200**	**3,400**	**5,450**	11,050	8,950	10,100	16,600	15,000	13,700	6,800	18,950	11,500 N (HMA)
	Flow (mm)[1]	1.25	1.50	1.25	1.25	1.25	1.75	1.25	2.00	2.00	2.00	1.75	1.50	2.0–3.5 mm (HMA)
	MQ (N/mm)	4,320	2,133	2,720	4,360	**8,840**	5,114	**8,080**	**8,300**	**7,500**	6,850	3886	**12,633**	3,286–5,750 (HMA)
Indirect Tensile Strength	ITS (kPa), Dry[1]	522	**276**	**370**	546	696	609	592	1,070	**498**	883	790	1,568	800 kPa (HMA)
	TSR (Saturation)[1]	0.95	1.13	**0.64**	0.85	0.90	0.99	0.89	**0.66**	**0.77**	0.86	1.05	1.06	TSR ≥ 0.8
	TSR (F.-Thaw)[1]	**0.56**	0.92	**0.36**	**0.62**	**0.63**	**0.65**	**0.76**	**0.42**	**0.67**	0.83	**0.69**	**0.75**	TSR ≥ 0.8
Cohesion	Remnants (%)[2]	**0**	**30**	**0**	**37**	100	100	**0**	**40**	**51**	85	94	100	Remnants ≥ 60%
	Remnants (%)[3]	**2**	**22**	**2**	**39**	100	99	**46**	81	**52**	95	98	99	Remnants ≥ 60%
Adhesiveness	Time (sec)[3]	**0.92**	**1.21**	**1.30**	**2.62**	**39.74**	9.31	**1.69**	**2.70**	**2.60**	**1.89**	5.46	**49.99**	5 ≤ Time ≤ 30

Note: Bold-Italic column heading = the best performing materials; Bold cell value = unacceptable material property

[a] = OGPCM; [b] = OGCCM; [c] = DGCCM; [d] = DGPCM; [1] = Cured at 135°C; [2] = Tested at 4°C; [3] = Tested at 25°C.

Chapter 5. Summary and Conclusion

5.1. Summary

Replacing copper cable with FO cable, which is capable of simultaneously providing voice, video and data services through a single cable, can meet the enhanced bandwidth demand for technologically advanced and widely popular internet services. Compared with traditional methods used in urban environments, micro-trenching technology (MTT) can result in quick, easy, inexpensive, and less disruptive FO deployment. To demonstrate MTT to the municipality and road users while meeting the desired installation standard, some CPs installed pilot projects and others opted for direct installation. However, most municipalities are reluctant to issue a permit for MTT since this method does not have accepted construction standards or specifications. Road authorities do not expect MTT to be a source of pavement deterioration and liability sharing when road reconstructions and rehabilitations take place. Additionally, severe weather conditions (more freeze and thaw cycles) may cause significant displacement in cable locations and may push the FO cable toward the pavement surface. Moreover, the performance of trench restoral materials applied in one area may differ from other areas where different climate conditions exist. In summary, any backfilling materials for northern climatic areas first need to be evaluated before applying them in large-scale installations.

In order to evaluate MTT performances (e.g., FO cable and backfilling), two pilot installations using two different MTTs (VIF and SMCI) were completed in Edmonton. The trenches of VIF technology were deeper than SMCI technology, and both technologies had different types of cable and backfilling materials. These installations have been under constant monitoring to measure the conduit movements and trench conditions. The seasonal inspections using GPR technology showed that FO cables moved a significant distance, and the cables of VIF technology showed more movement than those of SMCI technology; for both methods, cables installed under traffic paths had higher displacement than the cables of non-traffic areas. Visual inspections were conducted and found that the backfilling materials used in VIF installation had significant failures, and SMCI technology also had premature failures. Therefore, to minimize the conduit movements and to improve the backfilling performances, a modified MTT backfilling was proposed, followed by intensive laboratory investigations to determine the feasibility and field performances. In the proposed section, grout was recommended and tested for stabilizing the conduit in the base layer of pavement.

After analyzing the visual inspections' information, it was found that the CMA used in VIF technology had failures similar to the failures of cold patching materials. As micro-trenches are very narrow in size, HMA application and compaction become too difficult. A cold mix material with the least chance of experiencing patching failures would make the micro-trench restoration easy and quick. Therefore, various cold mixes (12) were tested in the laboratory, including PCM (OG and DG) and CCM (OG and DG), in order to evaluate the stability, moisture susceptibility, cohesion, and adhesion of these mixtures. Test results were compared with a HMA mixture. It should be noted that these test results can be used for other CMA applications.

5.2. Conclusion

As toady's internet-based services evolve with time and technological advancements, demanding high-speed infrastructures to increase bandwidth capacity by deploying ultra-fast broadband networks (e.g., FTTH) becomes indispensable. Hence, innovative, cost-effective, and efficient network (i.e., cable) installation methods are gaining enormous popularity among CPs. Among new methods, MTT is considered to be a promising alternative to traditional methods in metropolitan areas, where traffic is high, space is congested, subsurface utilities are over-crowded, and restoration costs are excessive. In contrast, MTT installations have faced several criticisms from municipalities and highway authorities for having poor quality installation, no deployment standard, high damage susceptibility, and potential impact on the pavement. Additionally, severe weather conditions may damage the installation, leading to adverse impacts on the pavement. In spite of this, road authorities expect MTT to be a durable method that maintains the pavement's integrity and longevity by following well-accepted construction and maintenance guidelines. Therefore, any MTT installation plans need to be tested in that region's weather and accepted by the respective authorities before following through on full-scale implementation.

To evaluate the performance of MTT installations in a northern climate, two pilot projects using two discrete MTT technologies (VIF and SMCI) were completed in Edmonton and monitored over two years. GPR and visual inspections were used to measure the conduit movements and assess the trench conditions. Some key findings are:

VIF technology:

- After six months of installation, including one winter, conduit in VIF Layout-3 had a maximum downward movement of 5.9 cm and upward movement of 14.3 cm, meaning more than 50% loss of conduit backfilling coverage. After 18 months, including two winter seasons, conduit had become almost horizontal with a maximum upward displacement of 8.9 cm compared to the original location.

- C6 and C7 had abrupt movements located near a 45° bend in Layout-3. Traffic loads, inadequate compaction of filling material, and adverse weather conditions could result in increased conduit movements in the loop layout compared to straight layouts.

- Observed reinstatement failures of the CMA-1 are ravelling (1–2 cm deep), cracking (0.2–0.5 cm wide), edge disintegration, and settlement due to the poor quality of patching materials and improper construction technique. The laboratory tests on the CMA-1 also revealed its poor stability, high moisture susceptibility, and poor cohesive and adhesive properties.

SMCI technology:

- Nine months after the installation date, the cable in Layout-2 had a maximum upward movement of 2.8 cm and downward movement of 2.6 cm, meaning the cable had lost one third of its cover.

- The highest displacements were found at the bends (e.g., 90° bend at E9), the intersections of two straight lines, which were increased by the traffic loads and exposure to adverse weather conditions.

- Backfilled material, especially hot-applied sealant, experienced settlement, poor bonding, and pulling-out failures. Highly temperature-susceptible and loose sealant failed to maintain strong bonding with the trench walls, pavement, and sand.

The combined MTT knowledge earned from the literature review, pilot installations, and field visits arrives at the conclusion that in freeze-thaw conditions, the conduit movements and trench restoration (of high quality) are the fundamental challenges. A modified MTT backfilling section is proposed to resist the vertical movement of conduit and to improve the quality of trench reinstatement while protecting the FO cable from any damage that may occur during road reconstruction and rehabilitation operations. Applying grout in the base layer is proposed to resist vertical movement of FO cable. The key findings of laboratory tests on grouts, ensuring feasibility and effectiveness, are:

- All three non-shrink and fast-set grouts had good flowability at their recommended moisture contents (e.g., Grout-1, 25%; Grout-2, 14%; and Grout-3, 18%).
- Grout had reasonably good coverage around the conduit, strong bonding with the conduit, low setting time, and very early and high strength gaining.
- When the trench temperature reduces and reaches freezing, the setting time of grout can remain short by applying warmer water. At freezing temperatures, the setting time was too short since the grout became frozen.
- After one day of curing, the compressive strength of the frozen grout samples reduced by 45% compared to the non-frozen samples. However, compressive strength became almost similar to the non-frozen samples after seven days' curing.

In modified MTT backfilling, applying CMA is suggested to fill the rest of the trench while maintaining the backfilling material's workability and durability. Twelve CMAs and a HMA were tested and compared for stability, moisture susceptibility, cohesion, and adhesiveness, and the key conclusions are:

- None of the CMAs satisfied all the required specifications of all measured parameters.
- Among the PCMs, OGPCMs had very poor properties with the exception of CMA-6 that only failed in freeze-thaw conditions. From the group of DGPCM, CMA-11 had acceptable properties, but it was susceptible to freeze and thaw cycles.

- Among the CCMs (OGCCM and DGCCM), only CMA-10 had superior material properties despite its poor adhesiveness.

- Careful consideration should be taken to select a suitable CMA, accounting for application type and climatic conditions. For example, CMA-12 may be an appropriate option for pothole patching in conjunction with using a tack coat layer, but its workability is not suitable for MTT micro-trenches.

- CMA-6 and CMA-11 mixes seem to be appropriate mixtures for both pothole patching and utility-cut backfilling, but not in cold regions that are subjected to freeze and thaw cycles. If this mixture is used for utility-cuts (e.g., MTT backfilling) in cold regions, using a sealant on top is highly recommended.

5.3. Future Research

This study provides laboratory tests results on both used and proposed MTT backfilling materials. Therefore, in order to monitor the long-term performance of the proposed MTT backfilling in field conditions, a pilot installation needs to be installed. As the monitoring of any pilot installation is a continuous process, the VIF, SMCI, and future trials (if there are any using a proposed backfilling) need to be observed for several years. The conducted tests on CMAs gave a good indication of the material properties, but the wheel tracking test as well as knowing the exact aggregate gradations of these mixes and their asphalt cement content (%) may help to make an informed decision during the material selection process for backfilling, patching, and other applications. Designing a suitable aggregate gradation of CMA and a mechanical compactor for MTT may enhance the compactability and performance, resulting in durable trench restoration.

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