Evaluation of Backfill Solution for Micro-Trenching in Cold Regions

by

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Abstract

In an era of innovative technologies and constant development, reliable and effective infrastructure is paramount. Fiber optic cable deployment, although extremely efficient, still lacks in infrastructure investment, preventing technologies like self-driving cars and G5 networks from being fully implemented. Micro-trenching is a three-step procedure that was introduced as a fast-paced and cost-effective solution to this constraint. The method consists of cutting and cleaning the inside of the trench; laying the cables and backfilling. Although micro-trenching has been successfully applied in many projects, there are still challenges to overcome. Backfilling materials must comply with a series of requirements, which include but are not limited to effectively bonding with the existing structure, providing structural support, and sealing the surface to water infiltration. Failing to satisfy such characteristics, can significantly reduce the service life of the technique. The small dimensions of the trench and the cold climate of Canada demand extra care, and this has been the topic of many studies since the introduction of micro-trenching in 2005.

The focus of this research is to assess different materials for use as backfilling for micro-trenching applications in cold regions. Studies began with laboratory tests to compare the resistance of regular and foam grout to freezing/thawing cycles. Specimens were cured for different time frames and conditioned in multiple cycles before being tested for compressive strength according to ASTM standards. The amount of absorbed water and failure mechanisms were observed for each sample in order to better understand reasons behind differences in performances. In the end, a material cost comparison was drawn based on each individual component of the mixes to provide information on the use of novel materials for industry applications.

In 2013, the University of Alberta and TELUS started a pilot study to address the short and long-term performance of micro-trenching applications. Existing trench configurations were performed by specialized companies, in addition to distinct backfilling materials and composite backfills proposed by the University after successful laboratory tests. In order to provide continuation to this study, visual observations were made to identify common pavement distresses that may have developed as a consequence of the trench installation, as well as ground penetration radar (GPR) analysis was conducted to locate and distinguish conduit movements inside the trench. Recommendations for future applications were proposed regarding issues observed during operation and novel materials introduced throughout the study.

Dedicated to

My wife, for the unconditional support in facing such a challenging situation while moving to a different country.

My entire family, for their love and care.

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1 Introduction

Telecommunications is a fast growing industry that is more vital in people's daily lives each day. Cisco (2017) estimates that global IP traffic will reach 3.3 ZB by 2021, representing nearly a threefold increase over five years. Of this traffic, more than 63% will be consumed by wireless and mobile devices. North America alone will account for 85 EB per month. Global fixed broadband speed will reach 53 Mbps, almost two times the 27.5 Mbps of 2016. Additionally, upcoming technologies like self-driving cars and 5G networks will also generate a high demand for reliable and cost-effective infrastructure. Catapult Transport System (2017) recommends that for safe implementation of connected and/or automated vehicles (CAV), a system capable of constantly providing fast updates is paramount. CAVs require at any given moment, information on other vehicles' position and speed, pedestrians, cyclists, weather, road conditions, and roadwork warning. Mobile data and ITS-G5 seem like promising solutions, but in either case the infrastructure necessary is still unavailable. Deloitte Consulting LLP (2017) estimates that to support wireless densification, serve rural geographies, and increase broadband competition, an investment of $130 - $150 billion over 5-7 years in fiber is required in the United States alone.

In this context, Steven Purcell introduced a technology known as micro-trenching in 2005. The technique is usually executed along the edge of roadways in order to avoid the wheel path of vehicles (Network Strategies, 2008). The process involves cutting and cleaning the inside of the trench, laying the cables, and backfilling. Proposed initial depths range from 8.9 to 10.1 cm and widths from 1.2 to 1.4 cm. Fiber optic cables are installed inside micro ducts, which sit in the bottom of the trench. A spacer approximately 25% larger than the trench is placed on top of the micro duct in order to ensure a tight seal and protection against environmental conditions.

Micro-trenching operates with the concept of causing minimal disturbance to the pavement and surrounding areas (Chorus, 2011). The small dimensions of the trench provide fast-paced and consistent deployment, at the same time offering decreased construction footprints and less risk to other utilities, which are usually located at a greater depth (Stahlbrand, 2012). In 2012, CityFibre concluded a state-of-the-art fiber to the home (FTTH) network of 21,000 homes in Bournemouth, UK. Micro-trenching was deployed for the distribution element, with a fully operational capacity of up to 4500 homes per month (Fiber to the Home Council, 2013). The

Magnificent Mile in the north end of Chicago accommodates a crowded subterranean area. Here, Electric Conduit Construction (ECC) opted for approximately 115 m of micro-trenching deployment as the solution for the increasing demand of the telecommunication industry in the area. Slim Lines Trenching installed more than 5 km of conduit in George Town, Cayman Islands in just four months. A depth of 30 cm was selected for the entire project in order to reduce risk of interfering with existing utilities (Schultz, 2011). By the end of 2018, over 100,000 homes in the County of Galway, Ireland will have access to fiber broadband (Open eir, 2018). Titan Communications & Networks is using SAFETRACK® micro-trenching solutions to run cables between connecting junction boxes, placed at 1 km intervals, along busy roads that can only be closed for short periods of time.

Although applied successfully in many cases, micro-trenching is not entirely free from its own challenges. Backfilling is a critical part of the application. The pavement needs to be reinstated, as much as possible, to its original condition in order to avoid premature failure (Stirling Lloyd Polychem, 2011); however, the small dimensions of the trench present a complication for compaction or vibration procedures. Thus, in order to create an effective bond with the existing structure, provide structural support and seal the surface to prevent water infiltration, the backfilling material requires good flowability, self-compaction, and adhesion properties (Stirling Lloyd Polychem, 2011). Additionally, the backfilling material should have the capacity to secure the conduit in the bottom of the trench, as this guarantees a reduced cost in maintenance services: movements inside the trench not only damage the conduit, but also result in cracks in the backfilling material (Hashemian, 2017).

Since the introduction of micro-trenching in 2005, much has changed in relation to the type(s) of backfilling materials used for this application. In the same year, a conference was held in Dundee, Scotland with the main purpose of introducing foam grout to construction practices. Among the many papers published in the conference proceeding was not only an introduction to the properties of the material, but also multiple test results to evaluate the material performance, as well as many successful case studies. In 2013, Allan Widger developed a comprehensive report on guidelines for reinstating trenches. In his report, Widger described the advantages and disadvantages of each material, from the perspective of the specific scenarios of each project. In addition to these solutions, pilot studies like the one conducted at the University of Alberta provide valuable data on the short and long-term performance of backfilling materials. From 2013 to 2016, a parking lot in Edmonton, Alberta was used to implement different micro-trenching loops, each containing a different setup of backfilling products. Research from this installation has yielded information such as cost and productivity analysis, pathology development, conduit displacement, and fiber cable integrity (Hashemian, 2017, Vaseli, 2017).

1.1 Objective

The objective of this research is to evaluate different materials for effective use as backfilling in micro-trenching projects. Following the success of field installations, regular grout and foam grout were studied in depth in the laboratory. Both materials were tested for the effect of density and freeze/thaw conditioning on compressive strength, flowability and capacity to consistently fill in voids, as well as the ability to protect and secure the cables inside the trench. A material cost comparison was made possible through a careful evaluation of all the individual components of each cement mix. Furthermore, a two- and four-year visual assessment of the pilot installation in Edmonton, Alberta was performed to detect typical pavement distresses. GPR analysis was also conducted to investigate cable movement inside the trench.

1.2 Methodology

This research was conducted in two individual phases: laboratory testing and service life assessment. The first phase was subdivided into two distinct studies. The first study focused on the evaluation of foam grout performance in cold regions. The laboratory analysis started by selecting a proper mix design to comply with micro-trenching specifications. After establishing the required material density, cylindrical samples were casted and submitted to multiple curing periods and freeze/thaw conditioning cycles. Specimens were tested for compressive strength according to ASTM standards to evaluate material performance before and after conditioning. Differences in test results were evaluated based on sample dimensions before and after conditioning and visual observations of failure mechanisms. The second study focused on quantifying improvement in grout mixtures after foam addition. Regular grout samples were submitted to the same performance tests used for foam grout mixes and the results were compared. Dimension measurements and crack patterns were used to better understand the reasons behind differences in performance, as well as a cost comparison was drawn based on the individual components of each mix.

The second phase consisted of a visual assessment and GPR analysis of a pilot test area in Edmonton, Alberta. This study was conducted in partnership with TELUS to evaluate the service life of different materials and configurations of micro-trenching application. Visual observations focused on typical pavement distresses that develop throughout the service life of the installations. GPR data was collected to locate and quantify movements of the conduit inside the trench. Since previous studies were conducted in the area with similar objectives, a performance comparison was drawn for each individual section and recommendations were made based on these observations.

1.3 Thesis Structure

The thesis has the following organization:

Chapter 1 – Introduction: In this chapter, the background, motivations of the research, objective, methodology approach, and thesis structure are provided.

Chapter 2 – Literature Review: In this chapter, the micro-trenching technique and foam grout technology are discussed in depth. Procedures, advantages and available literature are cited, as well as relevant case studies.

Chapter 3 – Laboratory investigation of using foam grout as micro-trench backfilling material in cold regions: In this chapter, foam grout performance in cold regions was evaluated using compressive strength results before and after freeze thaw conditioning.

Chapter 4 – Laboratory comparison between foam and regular grout performance in cold regions: In this chapter, the performance of foam and regular grout in cold climates was evaluated by comparing compressive strength results before and after freeze thaw conditioning, as well as completing a cost comparison based on material consumption.

Chapter 5 – Field evaluation of micro-trenching techniques and backfilling materials: In this chapter, the service life performance of different backfilling materials and micro-trenching configurations is compared, taking into consideration pavement distresses observed by visual analysis and conduit movements detected by GPR.

Chapter 6 – Summary and conclusions: In this chapter, the differences in materials' performance are summarized and explained. Field observations are synthetized, as well as possible future steps in the area and recommendations are envisioned.

2 Literature Review

2.1 Micro-Trenching

Micro-trenching is a three-step cable installation method used primarily for fiber optic (FO) cables in the telecommunication industry. The technique specifications have changed considerably since Steven Purcell's initial proposal; however, the main steps of the procedure persist to the present date. The initial stage involves cutting a trench along the edge of the road (Figure 2-1.a). Dry or wet cuts might be used at this stage as long as proper cleaning of the trench is provided after the operation (ITU-T, 1998). Such location is preferred to avoid direct load and pavement deflection caused by the wheel path of vehicles (Network Strategies, 2008). The size of the blade will determine the dimensions of the trench; industry applications have recorded widths ranging from 1 to 3.5 cm and depths ranging from 12 to 30 cm. The second step is to lay down the cables or conduits (Figure 2-1.b). It is industry practice to air-blow FO cables into ducts or conduits; a process that not only provides an extra layer of protection, but also allows for uninterrupted maintenance operations, as conduits usually contain multiple deployment paths. Securing the cable at the bottom of the trench is vital to prevent premature damages. In the last stage, backfilling is executed to reinstate the pavement surface (Figure 2-1.c). Countless products have been tested and used as backfilling in micro-trenching projects; but the success of the application depends upon the material having excellent bonding properties with the existing structure, providing structural support to the conduits or FO cables, and preventing any water ingression into the trench. Backfilling is the most important step in micro-trenching, as early pavement distresses will develop due to poor application (Stirling Lloyd Polychem, 2011).

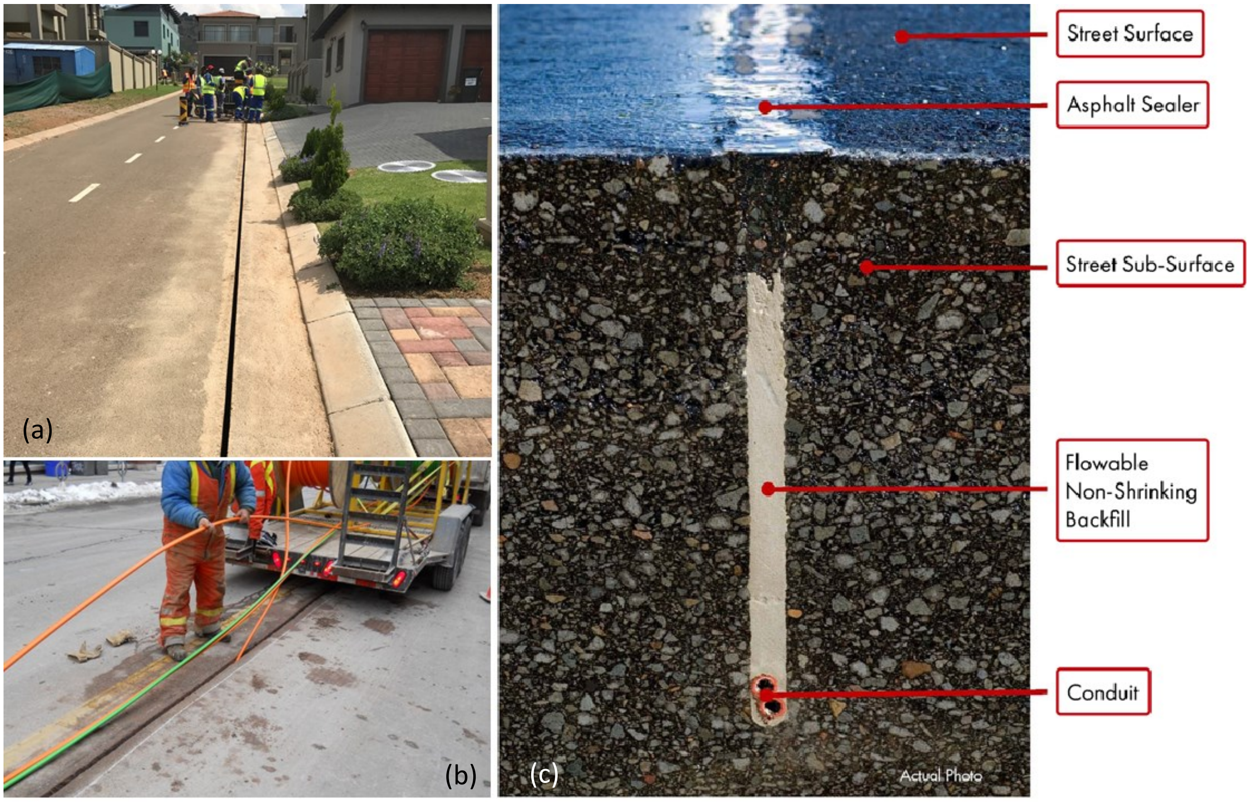


Figure 2-1: Micro-trenching application. (a) Cutting (Linteg Technologies). (b) Laying cables (The Fiber Optic Association). (c) Backfill cross-section (Certus View)

2.2 Advantages

The main advantage of micro-trenching and the impetus leading to the proposed technology is the concept of minimum disturbance to surrounding areas and existing buried utilities (Chorus, 2011). The trenches should have the minimum width required to fit the cables or conduits, and the depth should be shallow enough not to affect deeper utilities and deep enough to enable road preservation techniques like milling and filling. Due to such small dimensions, micro-trenching procedures are extremely fast-paced. Duraline (2016) estimates that savings in the order of 75% in time and 50% in construction costs can be realized during applications. Additionally, sections of the network such as the last meters of fiber-to-the-home (FTTH) and fiber-to-the-business (FTTB) are extremely challenging for typical open-cut or trenchless methods (Atalah, 2002). Micro-trenching can easily navigate the many disruptions in the fiber path that are characteristic of these sections. Finally, depending on the backfilling material used and the state of the trench after cutting, there is no weather limitation for the technique. The procedure can be executed year-round without negative effects on the quality of the application or constraints of installations in frozen soils.

2.3 Challenges

Much of the backlash that micro-trenching is facing in the construction community has direct relationship to the lack of a formal standard or Code of Practice for the technique. Local authorities encounter difficulties in assuming the risks associated with the technology, believing that trenching has the potential to damage and increase deterioration of the existing road by disturbing the structural matrix of the pavement (McDonnell, 2009). This interpretation shifts the attention away from the more concerning problem of poor backfilling in micro-trenching. A lot of quality control and evaluation must be applied during backfilling procedures, especially when testing novel materials. The small dimensions of the trench make it extremely hard to perform pouring, compaction or vibration, thus ideal products need to have excellent flow and self-leveling properties (Stirling Lloyd Polychem, 2011). Moreover, trenches are usually deep enough to reach different layers of pavement, which make it typical for different materials to be used in combination; typically in the interface between pavement and base layers (Hashemian, 2017). Projects in Canada confront an additional challenge when winter season are considered. Not only do freezing and thawing cycles provide an additional cause of deterioration, but not every product is designed to be applied in low temperature. As mentioned beforehand, the technique itself is not limited by weather conditions as long as proper material application requirements are being followed.

2.4 Previous Studies

In 2013, Allan Widger developed an extremely comprehensive guideline to reinstatement practices and programs commissioned by the public-private-partnership Communities of Tomorrow. Motivated by the high rate of failure encounter in trenching projects, especially within small municipalities, Widger’s work extends from the root causes of reinstatement failures and different materials selected to required principles for methods and equipment operation. Among the many materials evaluated, bituminous mixes were cited as having good bonding properties along with acceptable strength and bearing capacity; cementitious mixes were recognized for reliable strength, stiffness, and durability; lightweight concrete was presented as a flowable solution for areas with low soil stability; and geo-synthetics were considered an extremely useful product for areas with a high seasonal water table. At the end, a process flowchart was presented as a meaningful and effective instruction for trenching projects (Appendix B).

Since 2013, the University of Alberta has conducted extensive research on trenching and trenchless methods, with special attention to micro-trenching. In partnership with The Crossing Company, the City of Edmonton, NSERC and TELUS, students and staff associated with the Consortium of Engineered Trenchless Technologies (CETT) are devoted to providing a reliable source of information for industry practice in the sector. Experiments began by using the asphalt, aggregate and concrete laboratory facilities of the University to test the short and long-term performance of materials. After successful results, analyses were conducted in a field environment for service life assessment. A parking lot located at a TELUS operational building in the southeast region of Edmonton, Alberta was used to implement micro-trenching test loops with distinct trench configurations and backfilling materials. Multiple studies were published in prestigious journals and conferences from the information provided by this research. Among them, it is worthwhile highlighting the work of Hashemian (2018) in investigating the performance of cement grout, cold mix asphalt and epoxy grout in cold regions; Vaseli (2017) in using a simulation model to analyze the productivity of micro-trenching installations; and Hasanuzzaman (2018) in providing a thorough evaluation of properties of multiple cold mix asphalts available in the market.

2.5 Foam Grout

Commonly known as cellular concrete, foam grout is a lightweight form of concrete that is composed of a base mix (cement and water) and pre-formed foam. Two major categories can be used to describe the method by which a solution of water and foaming agent is transformed into foam. In the wet process, the solution is sprayed over a fine mesh, creating a low pressure zone across the mesh that is equalized when air is sucked from the atmosphere. In the dry process, the solution is forced through a series of high density restrictions using compressed air (Figure 2-2.a), expanding the material into a thick foam similar to shaving cream (Figure 2-2.b). Foaming agents can be either protein based, made from refined animal products, or synthetic based, made using the same chemicals as found in shampoo and soap. Foam grout also has two main methods of onsite production. Pre-formed foam can be injected into a half load mix wagon while the equipment is spinning at a fast rate. Alternatively, an inline system can be used to simultaneously input the base material and foam into a series of static inline mixers, blending the mix in a continuous process basis (Figure 2-2.c). The latter method is preferred in field applications due to the better reliability of obtaining a homogenized mix and the higher production outputs per trucks (Aldridge, 2005).

Figure 2-2: Cellular concrete production. (a) Foam dry method system. (b) Foam consistency (Thiessen Team, 2011). (c) In-situ application (Cematrix, 2018)

The ability to be produced and modified on-site is likely the biggest advantage of foam grout (Liew, 2005). A foam generator can guarantee a constant production of foam while the mix's density can be easily manipulated by the quantity of foam added. For foam grout, density and compressive strength are directly proportional (Jones, 2005, Kearsley, 2005, Liew, 2005, Ramamurthy, 2009). Such property creates a balance between the percentage of foam in the mix, and consequent volume expansion, and the strength requirements of each particular project. Liew (2005) provided insight on possible applications for the material based on different properties and density ranges. Low density materials were recommended for road sub-base over soft soil, as well as roofing insulation and fire breaks due to its thermal resistance. Medium density mixes were suggested for trench reinstatement, void filling and floor construction once it is extremely fluid, does not settle and requires no compaction (Figure 2.3-a). High density mixes are not considerably different from regular grout and could, therefore, be used as reinforced slabs and retaining walls. Additionally, the aerated constitution of the material is extremely effective for freezing/thawing resistance in cold region applications (Figure 2-3.b).

Figure 2-3: Details of foam grout (a) flowability (Cematrix, 2018), and (b) air void content

2.6 Conference in Dundee, Scotland

In 2005, a conference was held in Dundee, Scotland in an effort to close the gap in literature and specifications for production and performance of cellular concrete. The Proceeding 'Use of Foamed Concrete in Construction' reviewed a wide range of subject areas divided in two main themes: materials, properties and production characteristics; and specification for foam grout, applications and case studies. Among the many meaningful papers published, some deserve special attention considering the objectives of this particular research. Beningfield analyzed the mechanism of air entrainment in the mix. The effect of cement content, granular size and mixing time was quantified in order to introduce a steady method of producing consistent materials. Jones presented a thorough review of cellular concrete starting from constituent materials, characteristics and applications. Compressive strength, shrinkage, tensile/flexural strength, modulus of elasticity, thermal conductivity, permeation, durability, corrosion and fire resistance tests were conducted to develop a comprehensive guidance and specifications for construction practice. Finally, Kearsley investigated the influence of curing method and duration on the development of the material's strength for 56 days. A total of 7 mixes were prepared with different constituents and water/cement ratio, demonstrating the ability of cellular concrete to be a strong and durable material when well-manufactured.

2.7 Additional Literature

In 2009, Ramamurth compiled existing literature on the physical, mechanical and chemical properties of cellular concrete in a study to classify the constituents, mix proportioning and production of the material. Tests were summarized based on their results and specific characteristics of the mix, information that provided a more in depth and detailed knowledge of the subject. The lack of a standard mix proportioning was pointed out as a primordial concern for the manufacturing of stable mixes. In addition, the development of affordable foaming agents and foam generators was mentioned as being essential to the wide-spread utilization of foam grout.

The last study that was invaluable for this research was conducted by Tikalsky in 2004 with the objective of assessing freezing and thawing resistance of cellular concrete. By doing this, Tikalsky developed an alternative method to ASTM C666 for resistance to rapid freezing and thawing, a necessary modification considering the differences in water absorption and failure mechanisms encountered in cellular concrete. Tests were conducted for 7 distinct mixes and successful results created an excellent foundation for future studies.

2.8 Case Studies

A great number of diverse projects have successfully applied foam grout as a construction material. The following case studies have been summarized based on the specific area of service intended for the material.

2.8.1 Road Sub-Base

In 1998, a 228x13 m^2 area of poor soil was filled with over 9,000 m^3 of foam grout to provide enough bearing capacity to support the new toll booth facilities of the Illinois Tollway system. (Cematrix, 1998).In 2000, 200 mm of foam grout with 475 kg/m^3 density was placed beneath a 150 mm granular base course and 125 mm asphalt layer of a Light Rail Transit Bus Lane in Calgary, Alberta. The performance of this heavy traffic area was assessed in 2018 and no substantial distresses were encountered (Dolton, 2018). In a similar manner, three projects taking advantage of the lightweight properties of the material to support roads over soft organic soil (peat) were concluded in 2003, 2008 and 2009. Three km of a four-lane Central Road in Schaumburg, Illinois received almost 8,000 m^3 of wet cast foam grout for a full depth reconstruction, along with drainage improvements and curb installation. The 480 kg/m^3 material was produced onsite at a rate of 600-650 cm/day and resulted in a cost and time effective solution (Cematrix, 2003). The loading factor of an intersection at the City of Victoria was reduced by 5 after 500 mm of cellular concrete with a wet cast density of 475 kg/m^3 was placed beneath a150 mm aggregate and 75 mm asphalt layers (Cematrix, 2008). The excavation of 5 m of peat was avoided in Dixie Road, a rural area of Caledon, Ontario, by using 650 mm of cellular concrete over the subgrade. The road was closed for just over one week, reducing the inconvenience to the public and traffic constraints dramatically (Cematrix, 2009). Lastly, Dynaflect and Falling Weight Deflectometer data was collected in a trial section in Edmonton, Alberta to compare the performance of a sub-base layer of cellular concrete with a traditional granular section. Test results for the lightweight material were tremendously favorable and with a considerable decrease in the structural failures so often found in the region (Donovan, 2018).

2.8.2 Lightweight Fill

In 2002, almost 23,000 m^3 of cellular concrete was utilized in the renovation of Soldier Field in Chicago, Illinois, tosignificantly decrease the vertical loading on the foundation, reduce the amount of piling used, and limit differential settlement (Cematrix, 2002).In July 2006, more than 13,000 $m^3$of a mix (465 kg/m^3 and 0.55 MPa) were used at the playing field of the Mets Stadium in New York. The 1.5 to 1.8 m elevation of the old parking lot was conducted at a productivity rate of 765 m^3 per shift, which granted direct savings of more than $500,000 (MixonSite, 2006). Two foam grout applications were used to close the annular space and support a 1.5 m diameter water line, running a distance of 560 m underneath the North Saskatchewan River in Edmonton, Alberta. The excellent flowable characteristics of the material provided a fast paced application with no vibration or compaction required, allowing more than 3,000 $m^3$of the project to be completed in 3 days (Cematrix, 2007).

2.8.3 Structural Applications

In 1997, Cematrix built a replacement to two narrow bridges in Wasta, South Dakota. This projects was composed of 0.5 m of road structure on top of two layers of foam grout; the top one with 0.6 - 0.9 m of a mix with a density of 640 kg/m^3 and the bottom one with 0.6 - 1.2 m of a mix with a density of 480 kg/m^3. In total, the new structure used more than 6,000 m^3 of cellular concrete to provide less overburden on the structure and underlying soils. (Cematrix, 1997).The first application of cellular concrete in UK was conducted from 1989 to 2002 in Canary Wharf, London. Approximately 53,000 m^3 of the material were used to reduce the vertical load on the existing foundations and lateral load on the retaining wall along the road. (Cox, 2005).In 2001, the Kingston Bridge in west London, a heritage and heavy traffic structure was widened and strengthened. Two mixes of 1400 kg/m^3 and 600 kg/m^3 were applied to fill the void between the road level and the precast concrete arc shells. The solution was crucial to solve a huge traffic constraint created after a weight limit restriction imposed by local authorities (Aldridge, 2005).

3 Laboratory investigation of using foam grout as micro-trench backfilling material in cold regions

3.1 Abstract

Micro-trenching, an innovative method for fiber optic cables installation, involves creating a narrow trench in the road pavement to place a cable or conduit; the trench is normally narrower than 40 mm wide and shallower than 300 mm deep, depending on the size of the used conduit and trencher. After cutting the pavement, the next step is cleaning the area and placing the cable or conduit inside the trench, followed by backfilling. The quality of the backfilling plays an important role in both the sustainability of the installed cable or conduit and the cut pavement; using unsuitable materials or improperly installing cable or conduit can significantly decrease pavement life. The trench dimensions are very small, so for a successful procedure the backfilling material should be self-compacted and flowable enough to penetrate and completely fill the whole trench depth. As it has been investigated before, using traditional backfilling material such as play sand is not appropriate for Canadian cold regions; hence, it is recommended to stabilize the conduit inside the pavement's granular layer using a material similar to a cement grout. Alternatively, foam grout is a mixture of cement, water, and pre-formed foam; the foam considerably reduces the density of the blend by adding air, which consists of more than 25% of the mix. As a result, using this foam grout technology reduces the amount of cement required significantly and could be a cost effective solution for backfilling. The objective of this paper is to assess foam grout as a backfilling material for micro-trenching in cold climates. For this purpose, foam grout samples were prepared in a laboratory and their compressive strengths before and after several freeze and thaw cycles were investigated. Different mix-proportioning ratios were also studied in an attempt to create a more reliable method and assess variations in compressive strength and cost along with density.

3.2 Introduction and Background

Micro-trenching is a cable installation method that presents a reliable technique to the telecommunication industry due to its low cost, fast-paced execution, and more environmentally friendly aspects (DCMS, 2011). This cable-installation method is a cost-effective solution to time-consuming and disruptive traditional trenching methods, like open-cut (Atalah, 2002), especially when considering the logistics of the last 200 meters of fiber optic deployment, known to service providers as fiber-to-the-home (FTTH) (Duraline, 2016). Using this technique, a trench no wider than 40 mm and between 120-300 mm deep is created alongside the edge of the road; trenching closer to the curb is preferable in order to avoid direct load caused by vehicles in their wheel path (Network Strategies, 2008). The trench is then cleaned and cables are laid inside. The most important step of this method is backfilling. The pavement must be – as much as possible – reinstated to its original condition. However, the size of the trench poses a great challenge to this process. Materials used as backfill must secure the cable inside the trench and be self-compact, flowable, stable, properly bond with the existing structure, and prevent water penetration (Stirling Lloyd Polychem, 2011). It is important to note that the cut normally affects more than one layer of the pavement. Therefore, more than one material is usually applied as backfill. Figure 3-1 presents the three-step procedure for micro-trenching including cutting the trench (a), laying the cable (b) and backfilling (c).

Figure 3-1: Micro-trenching procedure (Rezai, 2016). (a) Cutting the trench. (b) Laying cable. (c) Backfilling

Micro-trench backfilling in cold regions presents a new challenge due to the unpredictable freeze and thaw cycles during changing seasons. With these extreme conditions, traditional materials like sand may not be suitable for backfilling purposes; for example, a pilot study investigation located in Edmonton, Alberta, Canada, used sand as a backfilling material in two different micro-trench techniques, and discovered that the cables had moved significantly (Hediyeh, 2016). With the first method, the 9 mm wide and 80 mm deep trench was completely filled with sand after the cable installation and covered with a hot sealant. With the second method, a 15 mm wide and 23 mm deep trench was filled with sand from the bottom to the interface of soil and pavement layers, and cold mix asphalt added on top. Monitoring the micro-trenches using ground penetrating radar (GPR) revealed considerable movements in the cables after a few months of installation (Hediyeh, 2016). Alternatively, in order to stabilize and protect the conduit inside the soil layer, cement grout was suggested as a replacement for sand. The setting time of the cement grout can be adjusted by changing the water temperature; additionally, the use of fast-setting cement will accelerate curing to less than 1 hour (Hashemian, 2017). The use of cement grout as backfilling material has some drawbacks, as grout compressive strength can be as high as 28 MPa after the first day of curing and may increase to 40 MPa after 28 days. These high compressive strength values compared to soil may lead to stress development on the interface of the existing material and the reinstatement product. In addition, the high cost of cement may make this solution uneconomical. To decrease the strength and lower the price of backfilling material, foam grout can be presented as reliable substitute.

3.3 Foam grout

Foam or aerated grout is basically a mix of cement, water, and foam. In foam grout, the air bubbles produced will act as a temporary wrapping material for the mortar (Liew, 2005). Foam can be generated by directly adding a foaming agent to the mix or it can be pre-formed in a separated recipient. In the dry method, a solution of water and foaming agent is forced through a series of high density restrictions by injecting compressed air into the mix recipient. The result is a thick foam similar to shaving foam (Aldridge, 2005). The density of the mortar can be controlled by the amount of foam added. Density ranges from 300 to 1,800 kg/m^3 can be obtained (Liew, 2005, Narayanan, 2000). However, care should be taken towards the material specification, as any decrease in density will directly decrease the compressive strength of the grout after curing (Liew, 2005, Narayanan, 2000, Jones, 2005, Kearsley, 2005, Ramamurthy, 2009). There is no defined mix proportioning for foam grout (Liew, 2005, Jones, 2005, Kearsley, 2005, Ramamurthy, 2009). The material specification is determined by collecting samples after each foam addition and controlling the density or strength (Tikalsky, 2004). The material is also very fluid, which provides an excellent load spreading and the ability to fill inaccessible areas without any compaction requirements (Liew, 2005). Other advantages of foam grout are that it does not settle, can be produced in-situ, and has great thermal insulation properties. All listed advantages guarantee successful applications for different purposes such as trench reinstatement, void filling, road sub-base, building construction, and roofing insulation (Liew, 2005, Jones, 2005).

Many projects have been conducted using foamed concrete as a construction material. In July 2006, 13,379 m^3 were used as a fill to elevate the playing field of the Mets Stadium in New York about 1.5 to 1.8 m above the grade of the old parking lot. A 465 kg/m^3 and 0.55 MPa mix was applied at productivity rate of 765 m^3 per shift, which provided a fast paced solution and direct savings of more than $500,000 (MixonSite, 2006). In 2003, 7,951 m^3 of wet cast foamed concrete was applied in a full depth reconstruction – along with drainage improvements and curb installation – of the 3 km, four-lane Central Road in Schaumburg, Illinois, USA. The area was facing ongoing settlement due to a soft organic underlying soil (peat) located 3 to 5 m under the roadway. The 480 kg/m3 material was produced onsite at a rate of 600-650 cm/day and resulted in a cost and time effective solution to the problem in the area (Cematrix, 2003). In a similar manner, both a 500 mm and a 650 mm layer of material was applied in an intersection of the City of Victoria in 2007-2008 and in a 120 m rural highway in 2009, respectively, to solve differential settlement caused by peat sub grade (Cematrix, 2008, Cematrix, 2009).

3.4 Objectives and Scopes

The objective of this paper is to complete and review a laboratory evaluation of foam grout minimum requirements for use as micro-trench backfilling material in cold regions. For this purpose, a mix design was prepared considering the material density and compressive strength. To evaluate the resistance of foam grout to freeze and thaw cycles, samples were conditioned and their compressive strength measured. To further prove the benefits of using foam grout as compared to regular cement grout, a cost analysis was prepared along with research and laboratory results.

3.5 Foam grout mix design

The mix proportioning method was developed by mixing 20 kg of Portland Cement Type GU at 1:2 water/cement ratio. Pre-formed foam with 5% protein-based foaming agent was added to the grout in small batches of 2 L (150 g). This value represents 0.17% in mass of the entire mix. After each addition, density was measured and three cylindrical samples were collected for compressive strength tests. The molds used have a 75 mm diameter and 150 mm height. Before the samples could be measured for density and tested for compressive strength, they were cured for 28 days inside a humidity chamber and the end grinded off. The procedure of preparing foam (a), mixing (b) and pouring (c) is shown in Figure 3-2.

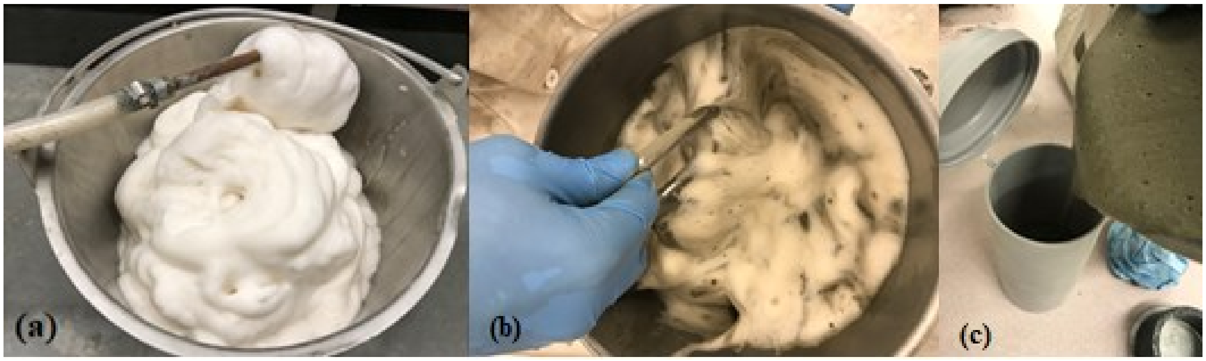


Figure 3-2: Sample preparation. (a) Pre-formed dry foam. (b) Mixing. (c) Pouring in the molds

The recommended grout strength after curing is 1-3 MPa (Chorus, 2011); in this research, to be on the safe side, the target compressive strength was selected between 3 and 5 MPa. After several tests, the corresponding density to this strength was calculated as 850 kg/m3. The density values obtained after each foam increment are presented in Figure 3-3.

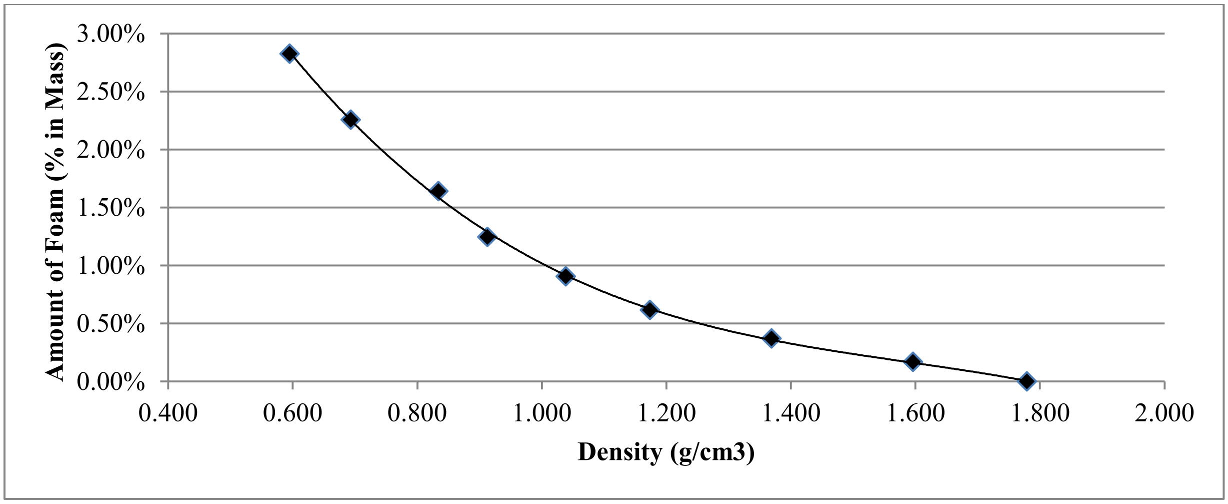


Figure 3-3: Mix proportioning curve

Figure 3-4 demonstrates the decrease in compressive strength obtained after decreasing the density of the foam grout mixture. As mentioned before, in foamed grout the air bubbles formed by the foam behave as aggregates in the mortar. Any increase in foam volume means more air inside the mortar and consequently, a lower density; that fact alone explains the compressive strength behavior as air has no measurable strength.

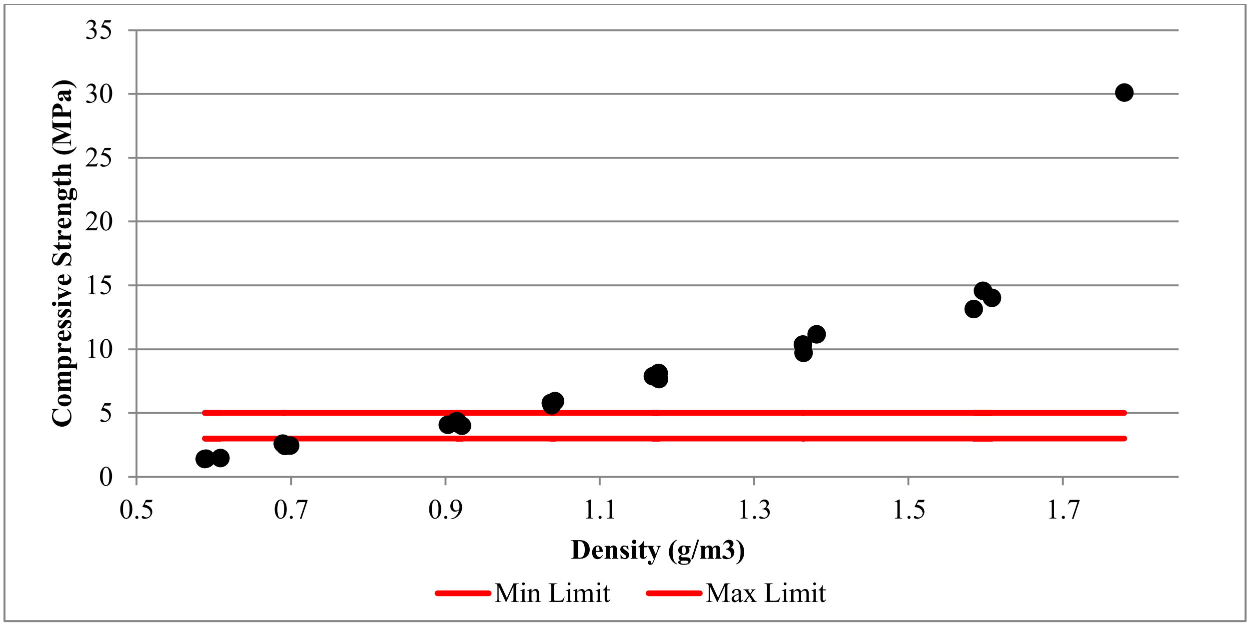


Figure 3-4: Compressive strength variations with density

Another interesting observation is that the simple addition of foam in any amount results in a plunge in compressive strength. For this experiment, adding 0.17% of foam in mass to regular grout caused the compressive strength to drop from 30 MPa to 14 MPa. Note that this reduction becomes way less steep after the first increment.

3.6 Freeze and thaw testing on foam grout

To evaluate the effects of density and freeze and thaw cycles in compressive strength, ASTM C39, 2017 procedure was followed. For the test, 62 foam grout samples with the density of 850 kg/m3 were prepared. Samples were cured in a moist room for 3, 7, 14, 28, and 56 days and submitted to freeze and thaw cycles. According to Kearsley and Mostert (2005), foam concrete continues to gain strength after 28 days of curing. Therefore, this curing period was added to investigate if the same happens for foam grout. Freezing cycles consisted of wrapping the samples in a plastic bag to prevent moisture loss and placing them inside an environmental chamber at -18˚C for 24 hours. For thawing, frozen samples were removed from plastic bags and submerged under water at 20˚C for 24 hours. Samples were conditioned to 0, 7, 14, and 25 freeze and thaw cycles for each curing period. After conditioning, samples were leveled using ASTM C 617 – 98 (2003) method and crushed in the compressive strength machine.

Figure 3-5 shows the compressive strength results after exposure to multiple freeze and thaw cycles. After 3 days of curing, the ideal target of 3 MPa for compressive strength was obtained. A steady increase in strength for 7 and 14 cycles was observed for all tested samples, reaching a maximum of 4.63 MPa for samples cured for 28 days and conditioned for 14 cycles; however, for cycle 25, a very clear distinction appeared between the samples cured for 3 and 7 days and the samples cured for 14 and 28 days. It was observed that in the early stages of curing, when the material is still building strength, the increase in density counter-balanced the deterioration caused by conditioning. Characteristically, in the last stages, the harsh environment prevails and the specimens begin to lose strength. The significant presence of air voids can be explanation for such a long period before those effects were noticeable in the samples. The crushed samples did not have a plain and clean cut typical of cementitious material, which could be indicative that foam grout might be able to stop, at a certain level, the progression of cracks. Further comparison with regular grout samples is suggested as a base point for this analysis.

In either scenario, an unexpected increase of strength was observed for all samples after conditioning, which demanded further investigation for a clear understanding. A deeper analysis of the specimens before and after conditioning revealed an increase in density, as observed in Figure 3-6. For each testing condition, identified as days of curing and freezing/thawing cycles, the results of the 3 samples were plotted in the graph. The circle and square points in the vertical direction represent the same sample before and after conditioning, respectively. Consequently, as observed in the previous test, once the samples become heavier, their compressive strength also increases.

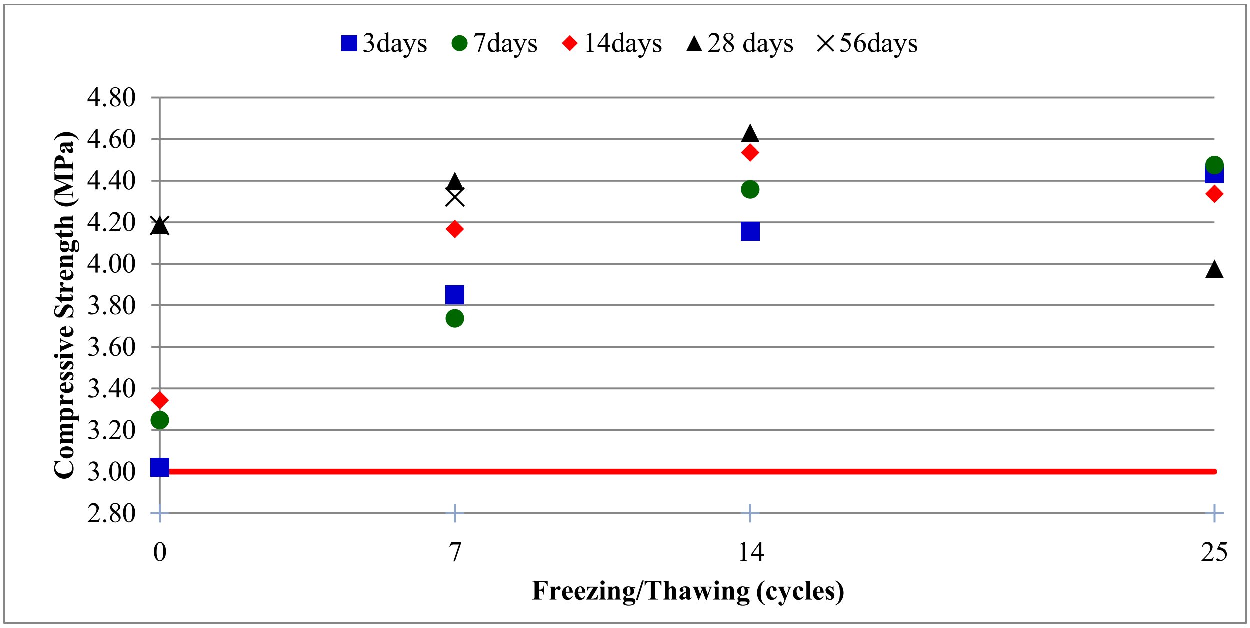


Figure 3-5: Compressive strength for regular and conditioned samples

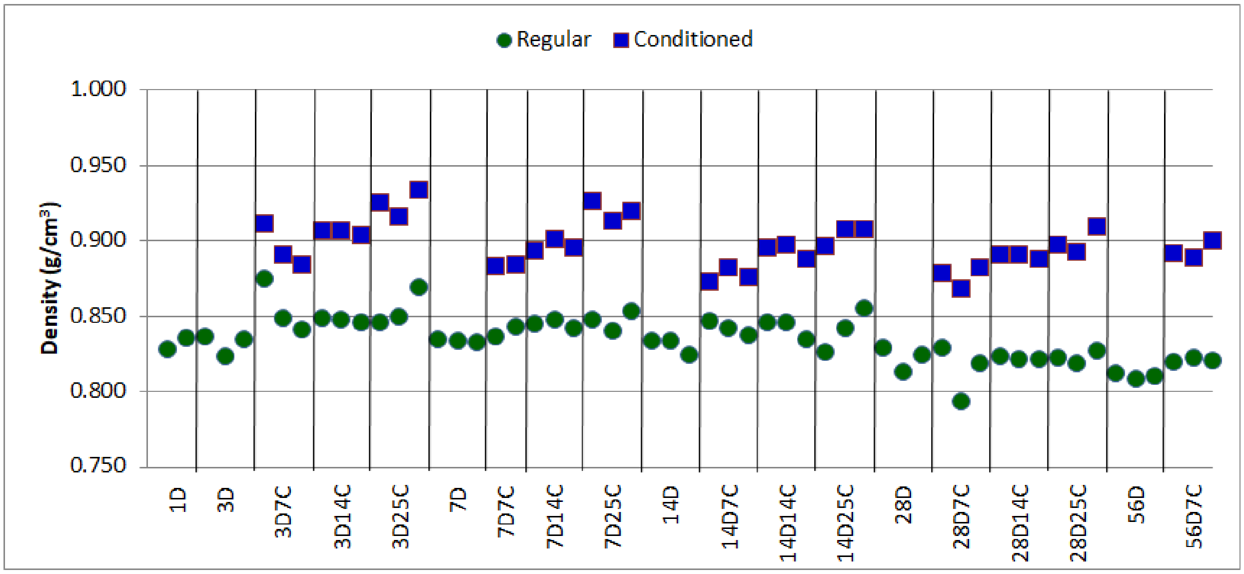


Figure 3-6: Sample density.

Future tests need to be conducted to closely evaluate the reasons behind this increase in density. Considering that every specimen was measured before and after conditioning and no difference was observed, the logical assumption would be that water is being absorbed by the samples and replacing the air within them. If water absorption is the sole test done to explain this density effect, then the results create a rather uniform pattern with the sample characterization. Figure 3-

7 shows the percentage increase in mass of each group of conditioned samples. These groups were selected based on the number of days the sample was cured (first number, e.g.: 3D) and the number of freezing/thawing cycles (second number, e.g.: 1C).

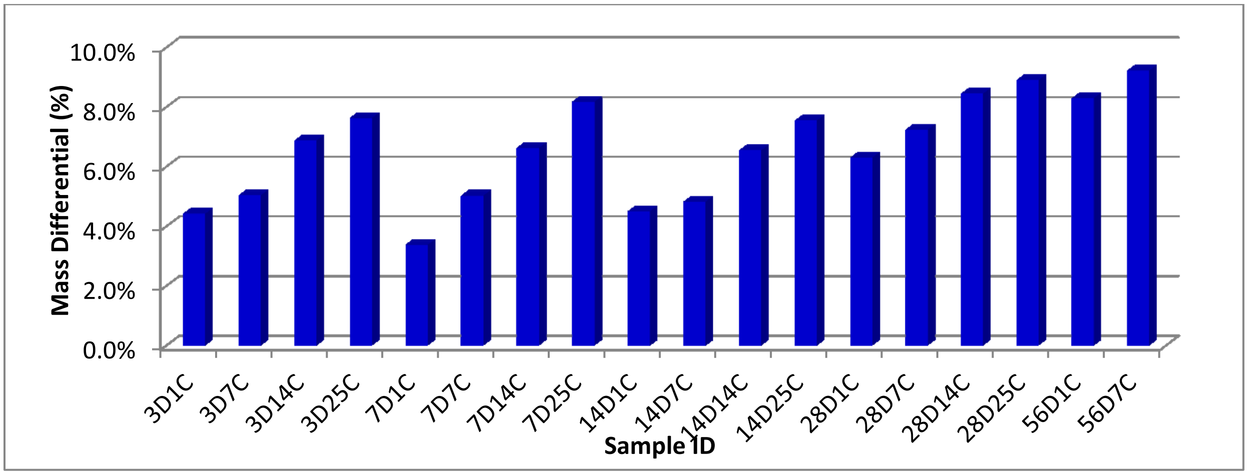


Figure 3-7: Increase in Mass

Corroborating with this theory, Figure 3-8 presents a distinct color difference between a sample that was submitted to freeze/thaw cycles (on the left) and one that was not (on the right). The darker gray shade clearly indicates the presence of water within the conditioned sample, despite the fact that the outside surface is bare dry. Additionally, the dimensions of each sample were measured before and after they were conditioned and no apparent differences were detected; hence, density increment could be a result of the sample's water absorption.

Figure 3-8: Water absorption samples before (right) and after conditioning (left)

3.7 Cost analysis of using foam grout

To prove the benefits of using foam grout, a cost effectiveness analysis of the material was conducted. Table 3-1 presents the savings obtained in regards to material cost with the foam addition and the corresponding density of the sample piece. For backfilling applications, the target compressive strength of 3 MPa can be obtained with a density range between 0.8 g/cm3 (6th increment) and 0.9 g/cm3 (5th increment). In this range, around 50% of cement costs can be reduced by foamed grout utilization in comparison with regular grout (blank).

TABLE 3-1: Cement Cost Saving with Foam Addition

Foam content (% in mass)	**0**	**0.17%**	**0.37%**	**0.62%**	**0.90%**	**1.24%**	**1.64%**	**2.26%**	**2.82%**
Average Density (g/cm^3)	1.780	1.596	1.369	1.174	1.039	0.913	0.834	0.694	0.596
Average Cost Savings (%)	0.0%	10.3%	23.1%	34.0%	41.6%	48.7%	53.1%	61.0%	66.5%

The results of this study prove that the foaming agent is inexpensive when compared to the cost of cement. In order to produce the first 2 L of foam, 1.25 g of the water/foaming agent mix was used. Considering the 5% ratio applied, the total amount of foaming agent was 62.5 mg. In other words, 1 L of foaming agent is enough to produce 20 L of water/agent mix, 800 L of foam and, consequently, 1.2 t of foam grout at 850 kg/m3 density. For perspective, foaming agent can be purchased in North America for an average of $10 USD/L (Cematrix, 2018).

3.8 Conclusions and Future Steps

Conclusions obtained from the study are summarized as follows:

1. As previous literature stated, there is a direct proportional relationship between density and compressive strength.
2. The simple addition of foam causes a considerable decrease in compressive strength that becomes less evident as the quantity of foam increases.

3. The addition of foam can significantly decrease the cost of other materials in any application.
4. Regarding foamed grout, freezing and thawing conditioning results in an increase in density, followed by a compressive strength increase after each cycle.
5. For short curing ages, this same increase in strength overcomes the deterioration of the material when submitted to freezing/thawing conditions.

Based on the above conclusions, it is advisable as next steps for the research to further investigate the reasons behind the increase of density after freeze/thaw cycles. Water absorption can be considered as a reasonable start point to conduct observations. In order to draw a comprehensive cost effectiveness study of the technique, production costs and productivity analysis can be conducted in field applications. Additionally, the existence of test sections like the one in Edmonton, Alberta represent a great source of information to assess long term performance of the application.

4 Laboratory comparison between foam and regular grout performance in cold regions

4.1 Abstract

Foam grout is a fluid, self-leveling and lightweight material with excellent load spreading and thermal insulation properties. These properties have made and continue to make foam grout be considered over regular cement/water grout counterparts in many projects. Although applied in many successful cases, not much has been done to compare foam and regular grout behavior in cold regions. This research focused on the compressive strength of both materials before and after freeze/thaw cycles. Specimens were cured for different days in a moisture room and conditioned for diverse freezing/thawing cycles to assess short and long-term performance. The impact of immediate freezing was also evaluated for both materials. Foam grout's ability to resist cold environments was explained using test results and visual analysis. At the end, a material cost versus strength analysis was conducted with the intent of providing a reliable source of information when selecting materials to fulfill minimum industry specifications.

4.2 Introduction and background

Concrete is the most widely used material in construction projects. The material is so reliable that the range of use varies from tall residential buildings and towers, down to structures' foundations, and across different roads, sidewalks and underground pipes (Fernandez, 2017). According to the Global Cement Directory and the Portland Cement Association forecast, the United States alone produced 120.5 Mt of cement in 2017 (Sullivan, 2016, Edwards, 2017). Although impressive, this number is still far from the estimated 1.5 Bnt production capacity of Chinese plants, of which lead the world in cement production and cement consumption (Edwards, 2017).

Cement grout is primarily used as excavation support, soil stabilization, foundation underpinning, and in groundwater barriers and general fillings (Hayward Baker, 2018, Cambefort, 1977). For example, in the southwest of Turkey in 2010, twenty 6 m holes were filled with 1:3 ratio cement/water mixture in order to prevent seepage from groundwater in an existing building (Akyol, 2010). In 2012, approximately 9,300 m of an 80 cm diameter jet grouting was implemented in Doha, Qatar to improve soil conditions of an off-shore sculpture plaza in the Museum of Islamic Arts Project (Zetas, 2010). Recently, in 2018, a side slope of a major highway in Iraq was improved with a 6% cement grout injection, resulting in observed soil swelling decreases of more than 90% (Daraei, 2018).

Cement usage in construction projects still considerably relies on an owner's preferences. In pavement applications, for example, there is a long standing discussion on cost differences between flexible and rigid pavements. Despite the fact that many case studies like Embacher's have already proven that the selection should be based on life-cycle cost analysis, and its results depend on the particular circumstances of the project (Embacher, 2001), the Asphalt Institute estimates that almost 94% of U.S. roads are paved with asphalt (Asphalt Institute, 2016). The increase in petroleum based products prices has been slowly closing this financial gap, but the concrete industry is also working on alternative materials to use on its final products. From industry by-products like fly ash, foundry sand and bottom ash (Siddique, 2014), to lightweight material (Liew, 2005), a lot is being developed to reduce concrete materials cost.

Commonly known as cellular concrete, foam grout is a lightweight form of concrete composed of a base mix (cement and water) and a pre-formed foam that has been used in the industry for road construction projects like tunnels, pipes, culvert grouting, utility insulation, backfill for retaining walls, spans, bridge abutments and approaches (Liew, 2005, Aldridge, 2005, Cematrix, 2018). Many properties of foam grout guarantee a successful application of said material in these projects; it does not settle or require compaction, has excellent load spreading and thermal insulation properties, is lightweight, very fluid, and adjustable during production to fit the customer's needs (Liew, 2005). In 1997, Cematrix used more than 6,000 m^3 of foam concrete to replace a bridge abutment granular backfill from the top and both sides of the structure down to the spring line of the super span arch. The new structure was composed of 0.5 m of road structure on top of two layers of foam concrete; the top one with 0.6 - 0.9 m of 640 kg/m3 and the bottom one with 0.6 - 1.2 m of 480 kg/m3. The application of a 25% lighter material was crucial to prevent settlement of the footings, which were built over soft underlying soil (Cematrix 1997). Similarly, the new toll booths of the Illinois Tollway system were built in 1998 applying over 9550 m3 of foam concrete. The 228x13 m2 area with depths ranging from 1.2 to 4.6 m sat over poor soil with not enough bearing capacity to support the facilities (Cematrix 1998). In 2002, the renovation of the Solder Field in Chicago, IL included an underground parking structure. Almost 23,000 m3 of foam concrete was applied to greatly decrease the vertical loading on the wall footing foundation, reduce the amount of piling used, and limit differential settlement (Cematrix, 2002). In order to support a 1.5 m diameter water line, running 560 m long underneath the North Saskatchewan River, 700 kg/m^3 of foam concrete was produced, providing 3 MPa compressive strength after 7 days. The annular space between the pipe and tunnel was filled with a 500 kg/m3 mix due to the excellent flowable characteristics of the material. The fast paced application and lack of vibration or compaction allowed the 3,100 m3 project to be concluded in 3 days (Cematrix, 2007).

North America's annual temperatures present a challenge to any material used in construction. Minneapolis' thermometers registered a low -25°C in January 2018. Canadian cities like Edmonton can reach temperatures as low as -30°C and remain in freezing conditions for more than 5 months. Laboratory tests such as ASTM C666-15 stipulate a durability factor that represents resistance of concrete samples to freezing and thawing conditions; however, as concluded by Tikalsky, more should be done in order to create a statistical database for foam concrete. In his work, he developed a modified ASTM method to evaluate the resistance of different cured mixes to freezing/thawing (Tikalsky, 2004). Considering his conclusion and the additional challenge that applications such as road sub-bases and trench backfilling procedures do not typically allow the entire 28 day curing period, the focus of this paper is on investigating and comparing the performance of regular and foam grout for cold region application.

4.3 Objectives and Scope

The main objective of this research is to evaluate the effect of freeze and thaw cycles on the strength of foam and regular grout mixtures. For this purpose, a mix design was developed to prepare samples for both materials. To investigate the impact of conditioning throughout different stages of application, samples were cured at different periods and subjected to several freezing/thawing cycles. Compressive strength of specimens was tested using ASTM C39/39M-17b. As a result of the laboratory investigation, the cost benefits of using foam grout material samples were calculated and a relationship between the saved material cost and compressive strength was determined.

4.4 Materials and mix design

4.4.1 Regular Grout

The cement grout was prepared using Portland cement type GU and water. The ratio was selected during the mix procedure with the main concern being the flowability of the material. Water was carefully added to the paste until it first reached a liquid state, which was observed at a water cement ratio of 1:2. A laboratory size mixer and plastic cylindrical molds were used to prepare 3 samples of 75 x 150 cm for each set of tests, which resulting in 62 samples total.

4.4.2 Foam Grout

The same base mix of regular grout was used to the prepare foam grout samples. A laboratory size foam maker with a production rate of 600 cm3/sec. was used to prepare a pre-formed dry foam; a solution made of 5% protein-based foaming agent generated foam with a 25 kg/cm3 density. Foam stability was evaluated according to drainage test for air void in concrete presented in the Federal Highway Administration (FHWA) report (Taylor, 2006). In order to select the appropriate density for the mix, a compressive strength versus density comparison was drawn. In this experiment, 2 L of foam were constantly added to a 30 kg base mix and density measured after each addition as shown (Table 4-1). Three cylindrical samples of 75x150 cm were casted after each increment and placed in a moisture room for 28 days of curing.

TABLE 4-1: Average density of foam grout after each foam increment

	Foam Addition							
(% in Mass)	0.17	0.37	0.62	0.90	1.24	1.64	2.26	2.82
(Liters)	2	4	6	8	10	12	14	16
Density (g/cm^3)	1.596	1.369	1.174	1.039	0.913	0.834	0.694	0.596

4.5 Compressive Strength

Compressive strength was tested based on ASTM C39/39M-17b. Regular grout had a minimum requirement of 50% loss in strength when compared to the specimen cured for the same time but not submitted to freeze/thaw conditioning. The samples were leveled using ultra coarse sanding sheet grit 60 and an aluminum level measure tool before testing. Once foam grout shifted to a more sensitive material, a capping method as described in ASTM C617 was used. This method consists of using a capping plate and a sulfur mortar to create a leveled cap in the specimens. The sulfur mortar is heated at 130°C and then poured into a capping plate. Samples are then carefully slid down the mortar following alignments guides found in the apparatus. All surfaces must be clean of debris and water to ensure a proper bond between the sulfur and the test specimen. As proposed by Chorus (2011), the limits of 3 to 5 MPa were determined as the acceptable limit for the foam grout strength. Test results are plotted (Figure 4-1).

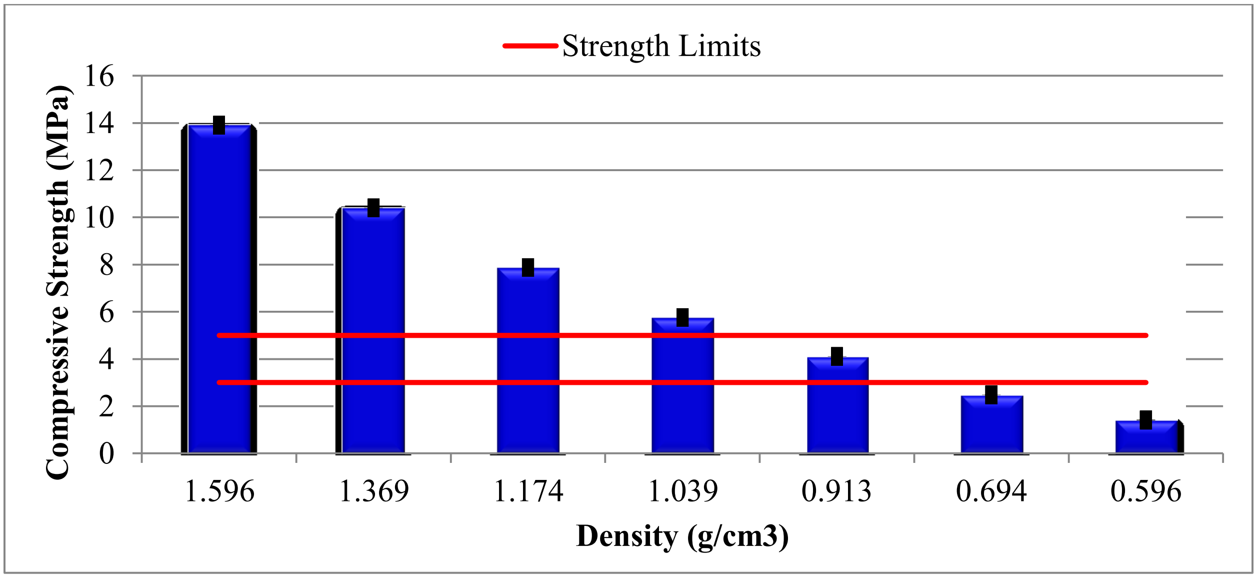


Figure 4-1: Compressive strength versus density

4.6 Sample Preparation

Based on the results, a density range of 850 to 950 kg/m3 was selected as the ideal values to achieve the required strength. Table 4-2 presents the total quantities of each component in both mixtures studied.

TABLE 4-2: Total quantities of components in the mix

Total Quantity	Material			
	Cement (kg)	Water (L)	Foam (L)	Foaming Agent (mL)
Foam Grout	40	20	39.4	49.2
Regular Grout	45	22.5	N/A	N/A

4.6.1 Curing

As aforementioned, when using grout in cold regions, it is important to investigate the impact of freeze and thaw cycles on the material strength before full curing. Therefore, different periods of 1, 3, 7, 14 and 28 days were considered for curing following the method described on ASTM C192 for compressive strength, flexural strength and specimens containing type III cement. A moisture room as specified in the standard was used to store samples, which were unmolded immediately after the completion of each period and conditioned with freeze and thaw cycles.

4.6.2 Freeze and Thaw Conditioning

Both regular and grout samples were conditioned according to the method recommended by Tikalsky (2004); this procedure is a modification of the ASTM C666 Method B, in which a freezing cycle represents a 24 hour saturated specimen at -18°C and a thawing cycle represents a 24 hour submerged sample at room temperature (20° to 23°C). Tikalsky method was selected based on the difference in failure mechanisms for foam grout, once it occurs from freezing of water inside the air pockets; and deterioration is not possible unless such pockets are sufficiently saturated (Senbu, 1990). Freezing was achieved by using an environmental chamber with capacity to reach -30°C and sealing the samples in a plastic bag to avoid excessive loss of moisture. Specimens were then removed from the plastic bags and placed in a container full of clean water for the thawing procedure. Samples were conditioned for 1, 7, 14 and 25 cycles for each curing period.

In cold weather applications, the grout material may sometimes freeze even before curing. To analyze the effect of early freezing, extra samples were cast and froze for 1 day at -18°C immediately after pouring in the mold. After this period, samples were placed in the moisture room and cured for 3 and 7 days.

A summary of the curing/conditioning periods is presented (Table 4-3), as well as the identification used for each sample. 3 replicates were casted for each individual analysis resulting in a total of 63 samples.

TABLE 4-3: Sample identification

Curing Time (days)	Freezing/Thawing (cycles)				
	0	1	7	14	25
1	1D	-	-	-	-
3	3D	3D1C	3D7C	3D14C	3D25C
7	7D	7D1C	7D7C	7D14C	7D25C
14	14D	14D1C	14D7C	14D14C	14D25C
28	28D	28D1C	28D7C	28D14C	28D25C

4.7 Test results and discussion

4.7.1 Compressive Strength Test

As expressed (Figure 4-2), the exposure to freezing/thawing conditioning before full curing deteriorates regular grout and reduces its strength significantly. Samples cured for 3 days lost their entire structural strength after 7 cycles of freezing/thawing. The conditioning effects for samples cured for 3 days throughout the entire conditioning process is presented (Figure 4-3). The results highlight the importance of a minimum curing period requirement for regular grout applications, once only the 14 and 28 days cured samples were able to comply with the 14 MPa requirement for up to 7 cycles. No samples resisted pass the 14th cycle of conditioning. At this point, the development of cracks throughout the specimens facilitates the entrance of water and the rate of degradation increases considerably.

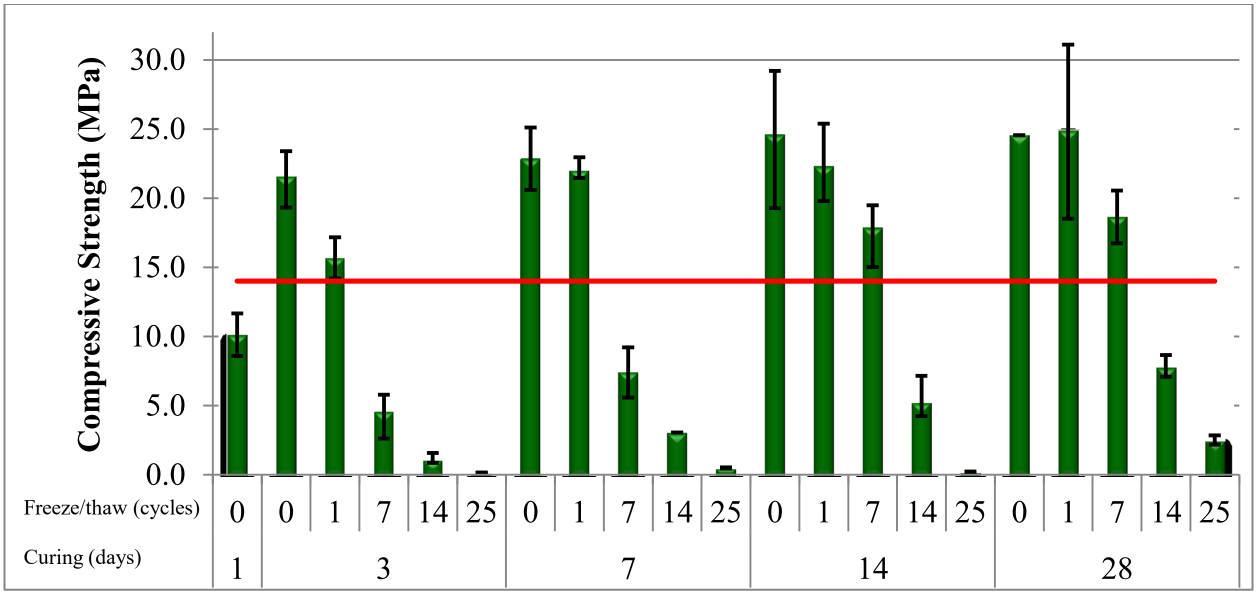
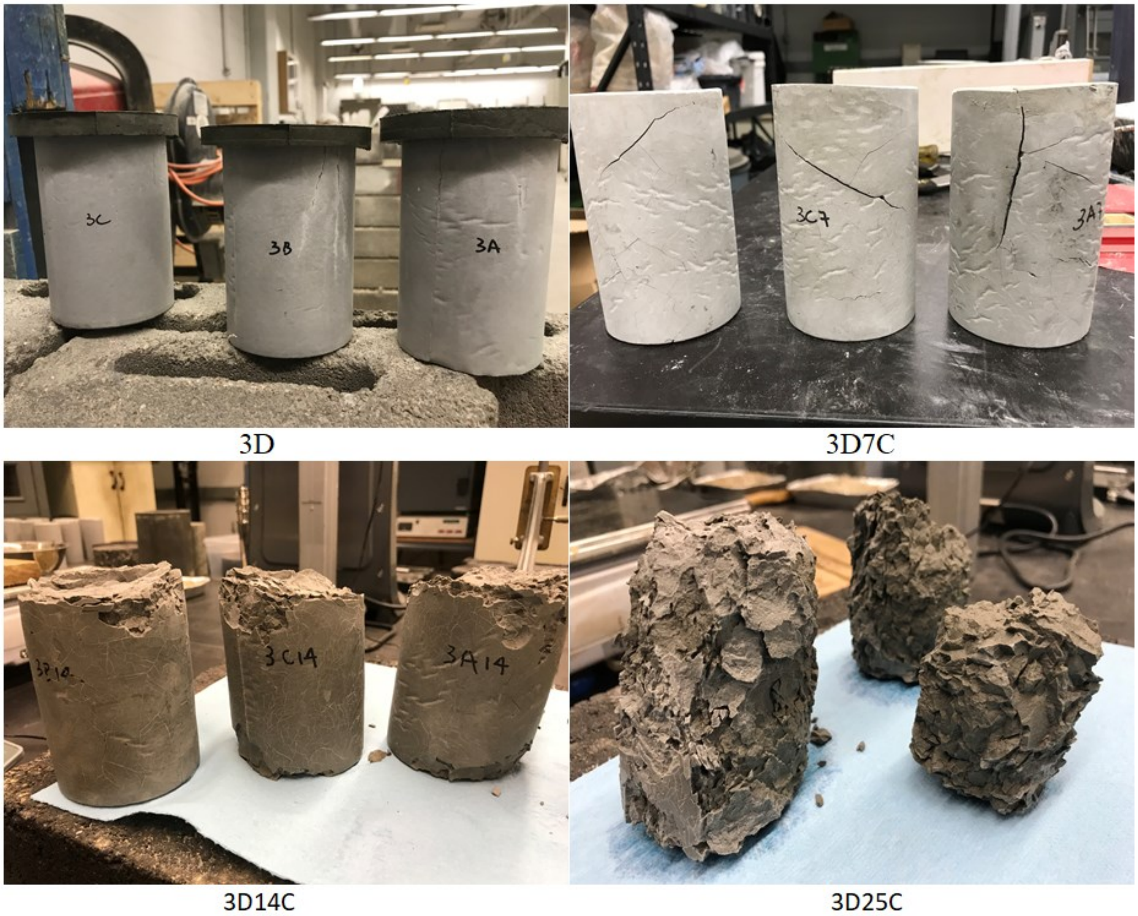


Figure 4-2: Regular grout compressive strength


3D

3D7C

3D14C

3D25C

Figure 4-3: Regular grout deterioration with freeze/thaw cycles

For foam grout, a completely different behavior was observed after subjecting the specimen to the same freeze and thaw conditioning cycles (Figure 4-4). By the 14th cycle of conditioning, every single specimen presented an increase in compressive strength. This trend is more evident for the early stages of curing, when the material is still building strength. Sample characterization revealed a gain in mass of all specimens. On the other hand, the 25th cycle exposed a clear contrast between the early stages of curing (3 and 7) and late stages (14 and 28). Despite the fact that the peak in strength of 4.6 MPa occurred at 28 days curing and 14 conditioning cycles, samples in early stages of curing continued the growing strength trend, while samples in late stages presented the first decline. It was observed that, during freeze/thaw cycles, the increase in density is beneficial to the material's strength once it counter-balances the deterioration of conditioning. This effect, however, can only be noted, as the material is not fully cured and before the last freeze/thaw cycles can be completed.

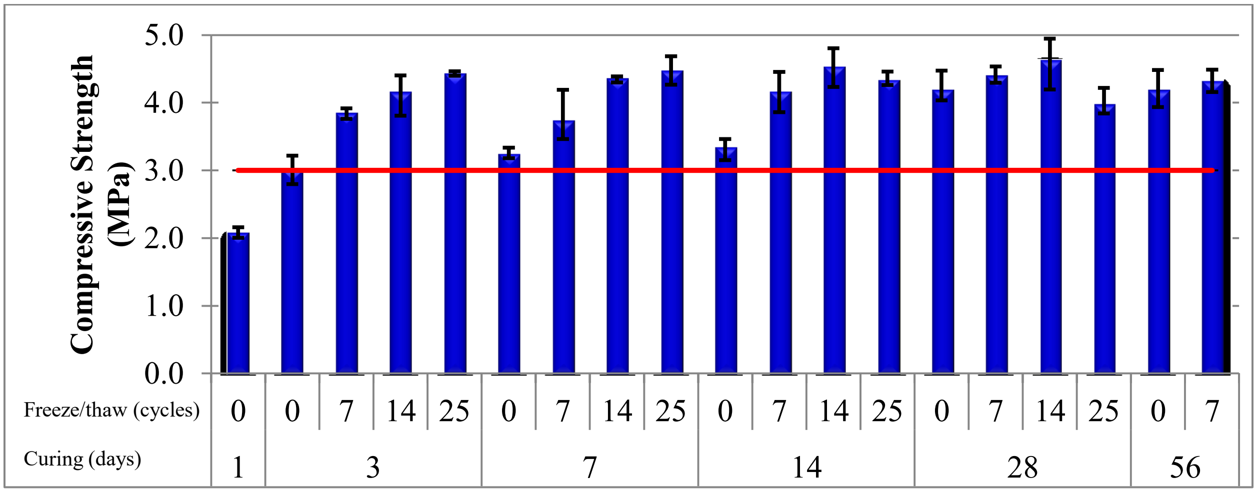


Figure 4-4: Foam grout compressive strength

After a thorough analysis of the possible reasons behind the increase in mass in foam grout and considerations with respect to the lack of changes in specimens' dimensions before and after freezing/thawing, water absorption was proposed as the most likely factor causing such weight gain. The work of Li (2012) was used to draw a trend of water absorption for each sample (Figure 5). This study proposes a normalization of the amount of absorbed water by dividing the change in specimens mass before and after conditioning for the surface area exposed to water. As expected, water percentages rise at the initial stages of freezing cycles and reach a plateau in the later, as well as specimens cured for longer periods absorbed a slighter higher amount of water during the hydration process. Despite the fact that the integrity of regular grout specimens prevented the reliable analysis of mass differences, the investigation still presents a fairly decent explanation for such contrasting results for both materials. For foam grout, water fills in the air voids within the sample, improving the material density and strength. Comparatively, for regular grout, the excess of water and lack of internal space during freezing cycles are extremely detrimental to the material.

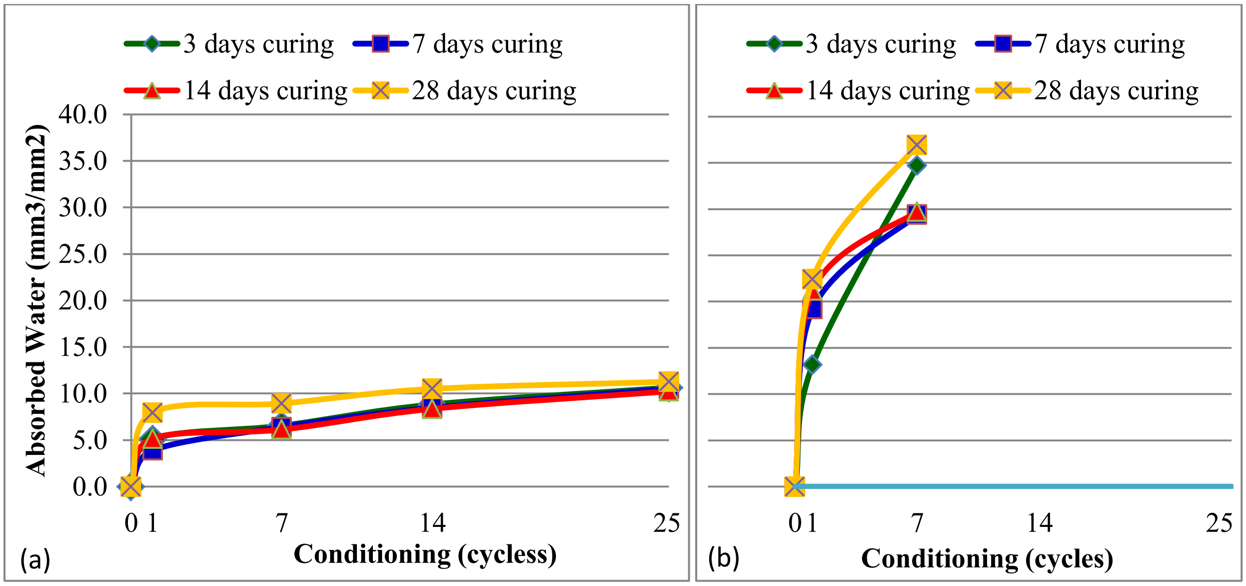


Figure 4-5: Water absorption. (a) Foam grout. (b) Regular grout

In order to compare the test results for regular and foam grout, all values were plotted in duration against a compressive strength differential graph (Figure 4-6). The base point was designated as the strength value of each cured sample in its regular state (not conditioned). In the most extreme case, foam grout specimens cured for 3 days had a 27.5% strength gain after 7 cycles, 37.6% after 14 cycles, and 46.7% after 25 cycles. For regular grout, the same 3 days of curing produced samples with a 27.2% loss after 1 single cycle, 78.7% after 7 cycles, 94.9% after 14 cycles, and 99.4% after 25 cycles.

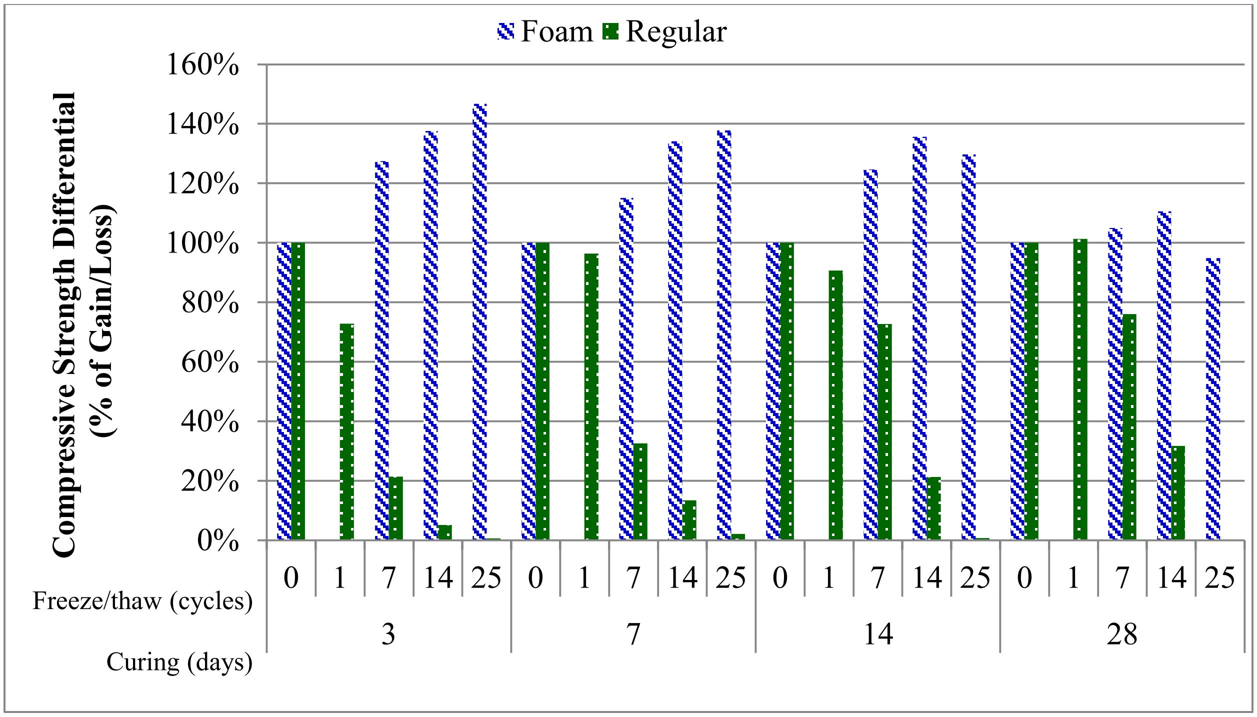


Figure 4-6: Compressive strength differential

Such behavior can be explained by the presence of air voids inside the material. During freezing cycles, water will expand inside the samples, and for foam grout, this water will fill existing spaces created by air bubbles, for regular grout, this expansion will generate cracks in the material from the inside to the outside. The damage observed in regular grout specimens is more significant for specimens that have short curing periods, due to the presence of excessive water in the mortar; in long conditioning cycles, the damage is result of the first crack creating an entry point for more water. Foam grout presented an interesting behavior in the sense that for short curing ages, while the material is still building strength, the increase in density observed after each conditioning cycle is beneficial for the material as a whole; however, as soon as curing was complete, specimens began to experience the wearing effects of freezing environments and started to degrade. Regular grout samples not submitted to conditioning cycles displayed the traditional clean and plain cut of cementitious materials, while conditioned samples were scattered like compacted aggregates. For foam grout, the propagation of cracks is disrupted due to the presence of air voids inside the samples. As soon as an air pocket is reached, the continuity of the crack stops and a new one needs to be formed until complete failure is established. With this material, all specimens displayed the exact same failure pattern and the only difference observed was the darker color shade in conditioned samples.

When immediately submitted to freezing, foam grout entirely restricts the ability to cure. After few hours the material shrinks and a hole develops in the middle of the sample. Curing proved to be inefficient once the specimens collapsed after thawing. Even though the regular grout samples withstand the entire procedure, compressive strength values reduced considerably. Specimens cured for 3 days recorded a strength of 2 MPa when compared to the 15.7 MPa obtained for samples cured for 3 days and conditioned for 1 cycle. While the samples cured for 7 days recorded 2.36 MPa when compared to the 22 MPa presented by the similar specimen.

4.7.2 Setting Time Test

One of the major concerns in construction is the closure period of working sites. Engineers need a clear understanding of minimum required times for materials to be applied and when the project site can be reopened; hence, setting time was calculated according to ASTM C953-17 for regular grout. The methodology consists of periodically inserting a 1 mm Vicat needle into the paste and calculating the elapsed time between the first contact of water and cement and the time when the penetration is measured to be 25 mm. Additionally, water was added to the base mix at different temperatures to address any possible improvement. Low and high temperature water was mixed at 5°C and 50°C respectively, as well as room temperature (20°C). The results for regular grout were 289, 293 and 312 min for cold, room and hot temperatures respectively. Although a small difference was observed, the use of alternative water temperatures is not recommended once energy is spent and no distinctive improvement is achieved. For foam grout, the test results were inconclusive. All samples tested failed to reach 25 mm of penetration in the first 6 hrs after casting. The high presence of air inside the samples is believed to disturb test procedure if testing is held off until it is easier for the needle to penetrate the mortar.

4.8 Cost performance analysis of foam grout material

One of the main interests of project managers directing construction projects is to select the most cost-effective material. Using foam grout instead of regular grout makes the material lighter and less expansive; however, the amount of foam should be adjusted to comply with the minimum strength requirements. The relationship between the material cost savings and material loss in strength upon adding different amounts of foam is shown (Figure 4-7). As observed, the addition of a small quantity of foam could significantly affect the grout strength. Additionally, the graph presents an increase in savings in cement cost that can be obtained at each increment in foam quantity, without sacrificing the compressive strength greatly.

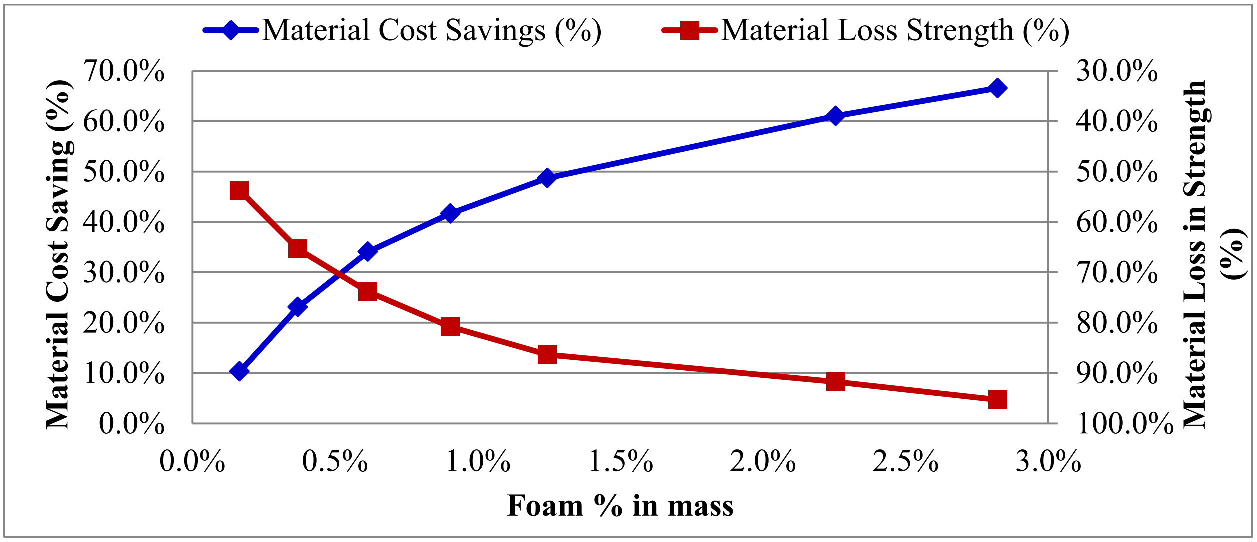


Figure 4-7: Cost versus strength analysis

For example, adding 1.25% in mass of foam could produce almost a 50% drop in material cost. At this density, a compressive strength of 4 MPa could still be obtained, which is reasonable enough for many applications. The foaming agent cost of $10/L is inexpensive when compared to Portland cement (Cematrix, 2018). In a ready mix truck of 8 m3 with a 900 kg/m3 density and 1:2 water to cement ratio, there is 2.4 t of water, 4.8 t of cement and between 3 to 5 L of agent, which results in a maximum $50 of foaming agent/truck. A mix truck with the same base mix for regular grout would contain 4.8 t of water and 9.6 t of cement. Another interesting observation provided by this analysis is the fact that the simple addition of foam in any quantity creates a high initial loss in strength. As presented, a 0.17% in mass of foam resulted in more than 50% decrease in strength with cost savings around 10%. Accordingly, there is a balance of cost and performance which is ideal for each specific project, as well as investigations similar to this can provide a reliable start point for research and improvement.

4.9 Conclusions

Conclusions obtained from the study are summarized as follows:

1. Regular grout requires a minimum of 14 days of curing and a maximum of 7 freeze/thaw cycles to maintain 50% of its original compressive strength, proving the material to be very sensitive to freeze/thaw conditioning.
2. On the other hand, foam grout shows signs of deterioration only after 14 days of curing and 25 freeze/thaw cycles, proving the material to be extremely resistant to freeze/thaw conditioning.
3. The existence of air pockets inside foam grout samples facilitates water entrance, causing an increase in density, and a consequent increase in compressive strength after each freeze/thaw cycle.
4. Failure patterns revealed a plain and continuous crack for regular grout samples not submitted to conditioning; a scattered surface for regular grout samples submitted to conditioning, explained by the continuous expansion/shrinkage of water inside the material throughout freeze/thaw cycles; and distributed cracks for foam grout samples, explained by the presence of air bubbles inside the specimens.
5. Foam grout will deteriorate if submitted to freezing conditions before setting, while regular grout will present a considerable reduction in compressive strength.
6. Cost versus strength analysis demonstrates that any addition of foam will significantly affect compressive strength and the balance between material saved cost and minimum required strength must be obtained specifically for each project.

4.10 Acknowledgements

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5 Field evaluation of micro-trenching techniques and backfilling materials

5.1 Abstract

Micro-trenching is a cable installation technique that is gaining prominence in the telecommunications industry for presenting a cost effective, fast-paced, and less disruptive solution to an increasing infrastructure deficit. In 2013, the University of Alberta started a project in partnership with TELUS to expand and improve micro-trenching applications by evaluating performance of distinctive procedures in a pilot test environment. The scope of this study is to assess multiple installed loops and their reliability for cold region applications. For this purpose, a thorough visual assessment was performed in every segment as well as GPR analysis was conducted to quantify conduit movement inside the trench. The entire area was subdivided into individual segments based on the particular details of each application; data was collected throughout the sections, as well as in special situations such as curves and extracted core samples.

5.2 Introduction

Micro-trenching is a three-step installation procedure for fiber optic cables at shallow depths that is gaining prominence in the telecommunication industry for presenting a reliable solution for fiber-to-the-home (FTTH) connections (Duraline, 2016). This technique introduces a cost-effective, fast-paced, and less disruptive alternative to a business that is overwhelmed with the necessity for infrastructure (DCMS, 2011). The initial stage in the micro-trenching is to cut the trench; the cutter's specifications will determine the dimensions of the trench, however typical values range from 1 to 3.5 cm wide and 12 to 30 cm deep (Network Strategies, 2008). The location closest to curb is preferable to avoid being directly located under the vehicles' wheel path (Network Strategies, 2008). Cutting is then followed by high pressure water cleaning, compressed air drying, and laying the cables. At this point, it is paramount to effectively install and secure the cables at the full depth of the trench (DCMS, 2011). Finally, surface reinstatement is performed as to guarantee a reasonable service life for the installation.

Many products have been tested and successfully applied in micro-trenching. Independent of the selection, backfilling materials must be stable, have enough fluidity to fill the entire volume of the small trench, and contain excellent bonding properties in order to prevent water penetration (Stirling Lloyd Polychem, 2001). Because the trench's depth is significant enough to affect distinct layers of pavement, it is common for different backfilling materials to be used in combination as reinstatement. Moreover, countries like Canada pose an additional challenge related to freezing and thawing seasons. Materials must not only be prepared for installation in frozen soils, but also endure potential frost heave caused by frost penetration and high water tables (Hashemian, 2017).

5.3 Background

In an effort to gather more information on the service life performance of micro-trenching, the University of Alberta developed a partnership with TELUS starting in 2013 to conduct a pilot installation in a parking lot of one of TELUS' operational buildings. The site contains different installation layouts, as well as backfilling materials as observed in Figure 5-1. Details of each individual loop are presented as follows:

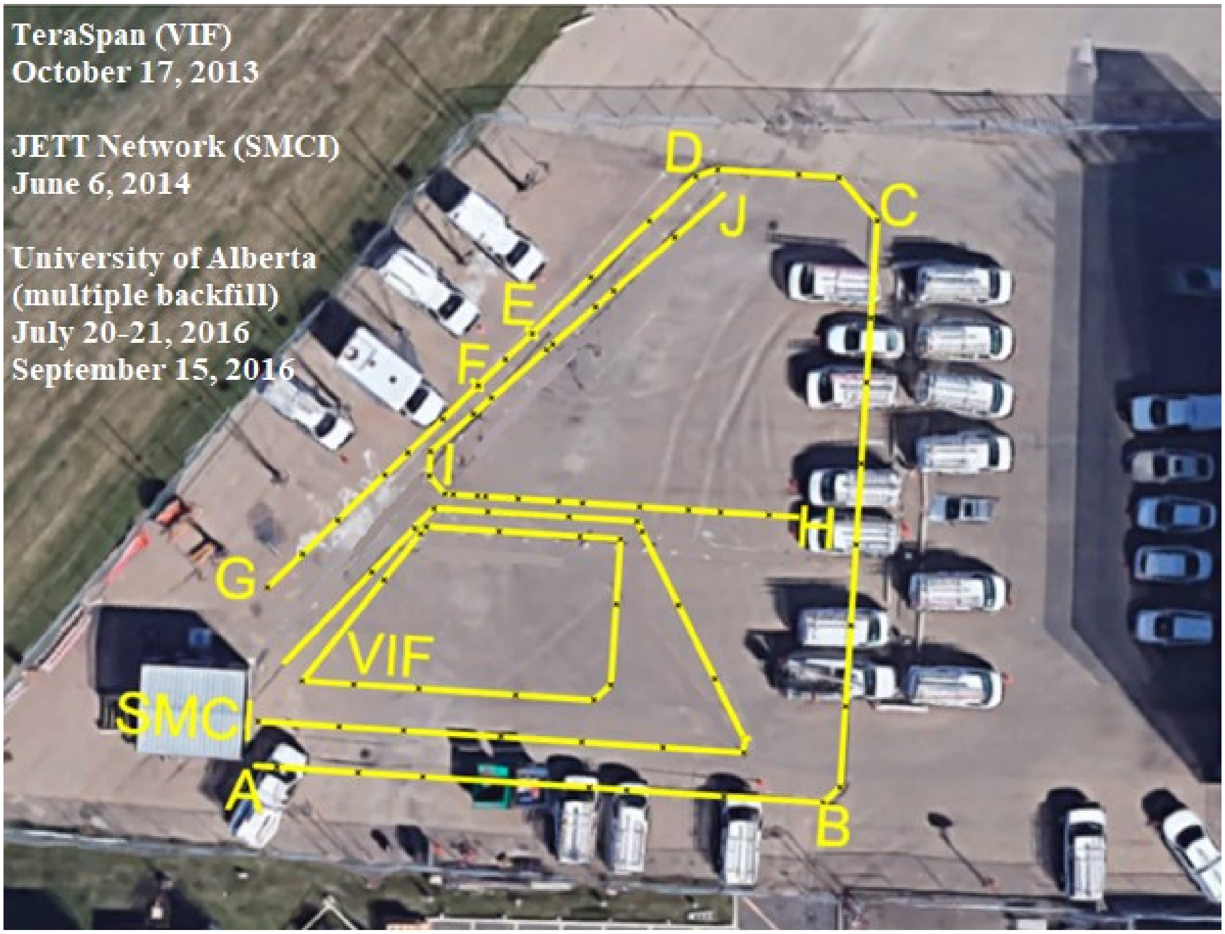

Figure 5-1: Schematics of site layout and construction dates

5.3.1 Vertical Inlay Fiber (VIF)

In October 2013, TeraSpan installed the first loop in the parking lot. VIF makes use of a zipper tool to fasten two conduits together and enclose a fiber optic cable, a technique known as Vertical Deflecting Conduit (VDC) (TeraSpan, 2013a). A concrete cutter digs a 23 cm deep and 1.5 cm wide trench, which is then backfilled with a 7.2 cm layer of sand, followed by a compacted layer of cold mix asphalt. The 115 m loop was concluded in an almost 19 hr duration utilizing one cutter and a two-person crew (Rezai, 2016).

5.3.2 Surface Micro Cable Inlay (SMCI)

In June 2014, JETT Networks installed the second loop. For SMCI, the fiber optic cables are inserted in a rugged central copper tube, which is protected by a thixotropic gel and a polyethylene sheath cover (JETT Networks, 2014). In this method a wet-cut trench is done creating a depth of 7.6 cm and width of 0.9 cm, of which is subsequently vacuum cleaned. A foam spacer and a rubber strip are positioned on top of the cable to secure it in place and prevent water ingress, and the trench is sealed with a 3.8 cm layer of sand and a 1.3 cm layer of hot bitumen sealant. The 102 m loop was concluded in a 7 hr duration utilizing one cutter and a two-person crew (Rezai, 2016).

5.3.3 University Installation

In June and September 2016, the University of Alberta decided to install new loops to evaluate the performance of different backfilling materials. The installation was subdivided into sections according to the material used.

5.3.3.1 Composite Backfilling

A total of three sections were reinstated with a composite backfill of grout, cold mix and bitumen sealant. The segment A-D is an 82 m section that was backfilled with cold mix asphalt on top of a Type GU cement mix with 25% of water content. Segment D-E contains 16 m of extension and was reinstated with a layer of cold mix asphalt on top of cellular concrete with the same 25% of water content. Lastly, segment E-F was backfilled with an initial layer of fast setting concrete with 20% water content, followed by a layer of cold mix asphalt. This section has a total length of 4.5 m. In all aforementioned segments, grout mixes were filled up to the intersection between asphalt and base layers, while cold mix was applied and compacted in the remaining part (Rezai, 2016). A hot bitumen sealant was applied on top of the trench to prevent water ingress.

5.3.3.2 Grout Reinstatement

In order to properly evaluate the interaction between cementitious materials and the existing asphalt layer under direct load, segments F-G and H-I were filled with grout mixes up to the top of the trench and sealed with a hot bitumen sealant. The first represents an 18 m section filled with Type GU mix, while the last is a 22 m section with cellular concrete. Using grout as a single backfilling material allowed the crew to save a considerable amount of time during construction, as pouring can be executed in a continuous process, and no compaction is required (Rezai, 2016).

5.3.3.3 Laboratory Alternative

Finally, an alternative method was proposed as a fast-paced application as well as a solution for the bonding requirements of backfilling materials. The process involved filling the trench with a uniformly distributed fine aggregate and pouring a polymer modified emulsion until the trench was completely filled (Rezai, 2016).

5.4 Objectives

The objective of this paper is to provide a service life assessment of micro-trenching in cold regions. For this purpose a visual observation was performed in the aforementioned application with focus on settlement, bonding with existing structure, and typical pavement distresses. Additionally, ground penetrating radar (GPR) technology was used to evaluate cable movement inside the trench.

5.5 Methodology

For the purpose of this research, each backfilling material will be referred to as the segment in which they were applied. Visual assessment was carried out in September 2018 with the objective to identify common distresses in the pavement area surrounding the micro-trench such as cracks, poor bonding, settlement, raveling and disintegration. As of this date, the time frame of each analysis is presented in Table 5-1.

TABLE 5-1: Time frame of GPR analysis

	Identification							
	VIF	SMCI	A-D	D-E	E-F	F-G	H-I	J-I
Service Life (years, months)	4, 11	4, 3	2, 3	2, 3	2, 3	2, 3	2	2

Ground Penetrating Radar (GPR) is a technology used mainly for localizing underground or covered utilities by sending a pulse of energy into a material and recording the time and strength necessary for this signal to be reflected back to the original source. Such reflections are made possible because different materials have distinct electrical conduction properties or dielectric permittivity. The higher the amplitude between these properties, the stronger and clearer the signal observed (Geophysical Survey Systems, 2016). Figure 5-2 (a) presents the schematics of a signal reflection as well as the distinction between different materials.

Data collection in the field started with calibration of the equipment. By calibrating the horizontal and vertical distance traveled by the antenna and the energy pulse in a test section of known parameters, the dielectric properties of the studied material can be calculated with a high level of confidence. Such dielectric values can then be used in the pilot application to estimate with a fair amount of certainty the depth of cables inside the trench.

Data points were collected every 3 m for sections D-G, every 5 m for the remaining sections, and in every particular scenario, of which included curves in the trench path as well as core samples extracted from previous analysis. By crossing the trench in a perpendicular direction, the subtle change in material properties presented by the cable can be easily identified by the software as a hyperbole, seen here in Figure 5-2 (b). The peak of this hyperbole indicates not only the moment when the antenna was sitting right above the cable, but also the exact depth of the cable inside the trench.

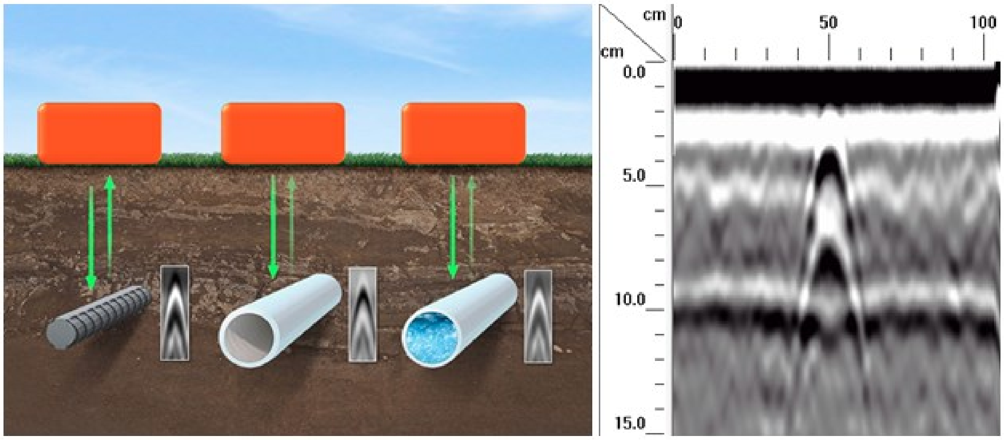

Figure 5-2: (a) Schematics of signal reflection (Gssi, 2016). (b) Software representation of data collection (Gssi, 2016)

5.6 Visual assessment

5.6.1 VIF

The VIF technology presented a fair to poor performance considering regular pavement distresses. The absence of sealant assists the technique in blending with the existing structure. From a user point of view the trench is barely noticeable, but it facilitates the ingression of water. Alligator cracks and permanent deformation was found in the entire surrounding area of the application, which is a consequence of excessive water in the granular base layer. Guaranteeing that mud from the cutting process is not present during backfilling and ensuring that proper tack coat is applied to the walls of the trench is a reliable method to mitigate such distresses without having to consider sealant applications. Some settlement was observed along the trench, although the trench deformed in a same manner and quantity as the pavement around it, which is a good sign in reducing stresses in the interface between backfill and existing structure (Figure 5-3).

Figure 5-3: Distresses encountered in VIF segment

5.6.2 SMCI

Considerable settlement was encountered in the entire length of the SMCI application, and was especially severe in the curves of the trench path. Sand has been proved to be a poor backfilling material in past literatures due not only to the inability to secure the cable, but also to how easily the material can be densified or simply washed away from inside the trench (Rezai, 2016). Either excessive use or lack of sealant were mistakes committed during the application, resulting in pathologies later on. Furthermore, sand and existing asphalt edges provide a weak bond with the bitumen sealant, of which was a main cause of the pulling-out failures observed (Figure 5-4).

Figure 5-4: Distresses encountered in SMCI segment

5.6.3 Grout + Sealant

Both scenarios in which grout was backfilled up to the top of the trench and sealed with bitumen sealant presented a considerable amount of cracks and heaving; these observations were intensified in the regular grout section due to the compressive strength and rigidity properties of the material. Once adhesion between bituminous and cementitious materials is fairly poor, continuous freezing and thawing seasons generate cracks in the interface of both materials and allow water to entrain the trench. During winter, this water freezes and expands, forcing all materials to shift in the trench. Grout backfill, unlike the asphalt and granular base layers, does not have room to accommodate these movements, which results in heaving and consequent expansion of cracks in the sealant. In the foam grout segment, this expanding and shifting process was less significant as the strength values are closer to the surrounding materials, and the air pockets inside the mix can withstand a certain degree of deformation (Figure 5-5).

Figure 5-5: Distresses encountered in grout + sealant segments. (a) F-G. (b) H-I

5.6.4 Aggregate + Emulsion

A considerable amount of problems arose from this type of backfill. It is difficult to determine the exact amount of emulsion required to fill the trench, resulting in segments where emulsion overfilled the trench and spread around the pavement and segments where there were gaps inside the material that later caused settlement. Two years have passed since the application and the material is still extremely soft. The excess of emulsion not only caused bleeding around the trench but it also made the material considerably fluid. A core sample was extracted from the field and kept inside a receptacle. After a few hours, the material spread throughout the receptacle accumulating in the bottom and leaving an empty space in the trench (Figure 5-6).

Figure 5-6: Distresses encountered in the aggregate + emulsion segment (I-J)

5.6.5 Grout + Cold Mix + Sealant

Grout and cold mix proved to be the best combination evaluated. The cold mix bonds extremely well with the asphalt layer of the pavement when tack coat and compaction are performed properly. Different types of grout performed differently, but well enough to secure the cable in place and fill the entire extension of the trench. Small cracks were observed in the sealant, especially in the regular grout section. The large difference in compressive strength values creates a weak point in the interface of the backfilling material and the existing structure. Foam grout is less susceptible to differential displacement as its compressive strength values are closer to the other materials in the surrounding area. Fast setting and regular grout are fairly similar materials; however, care should be taken with the first during application so the material does not set before pouring is complete. Settlement was noticed in most curved sections in the trench path. Considering that those segments were not submitted to any special load or conditions, defects during application are believed to be the main cause of such distresses. Overall, these areas presented good results and very few distresses were observed (Figure 5-7).

Figure 5-7: Distresses encountered in the grout + cold mix + sealant segment (A-F)

5.7 GPR results

The inability of backfilling materials to secure the conduit in its original position is a concerning problem, as any bending might damage the cables therefore affecting functionality. Such property is vital especially after freeze/thaw cycles, when the upwards and downwards movements are at a peak level. GPR analysis revealed a consistent value of 5.42 for the dielectric of the studied pavement section. It is important to note that it rained in Edmonton the day previous to data collection and the presence of water is known to cause distortion in the signal as well as increase the materials' dielectric (Geophysical Survey Systems, 2016). The results obtained were plotted based on the distance traveled along the trench for each individual segment and the respective depth of the conduit as presented in Figure 5-8. Segment I-J has no conduit in the initial 10 m and no observations were made up to this start point.

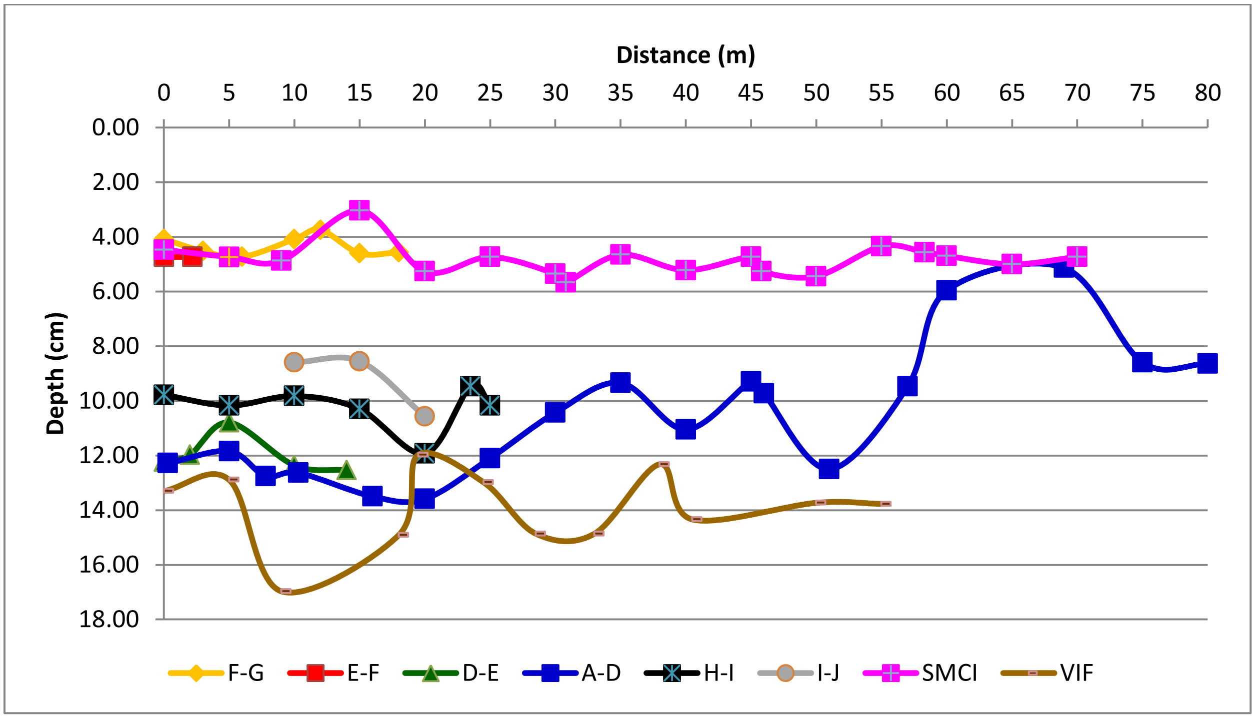

Figure 5-8: GPR data for September 2018 analysis

Differences in depth along the trench are result of the initial position of the conduit when first installed, as well as possible displacements with service life; therefore, comparison with previous year's analysis is crucial to separate distinct root causes and evaluate the materials' performance.

5.8 Comparison with previous years

5.8.1 TeraSpan (VIF)

VIF presents the worst scenario when conduit movement inside the trench is considered. Since its initial installation in 2013, the conduit has moved considerably inside the trench in both an upwards and downwards direction, despite the fact that progressive analysis has shown a tendency of movements towards the surface. The second curve in the loop proved to be the most sensitive point. Placed at an approximate depth of 22 cm in 2013, the conduit has since moved upwards to 11.13 cm, upwards again to 9.93 cm, downwards to 16.09 cm, upwards to 10.17 cm, and finally downwards to its most recent position at 12.98 cm of depth. Even more concerning, differential movement was observed in fairly short distances, which is extremely likely to cause damages to the fiber optic cable. Such observations further prove sand's inability to secure the conduit not only down the trench but at an even depth. Figure 5-9 shows GPR analysis performed throughout different years in the VIF loop.

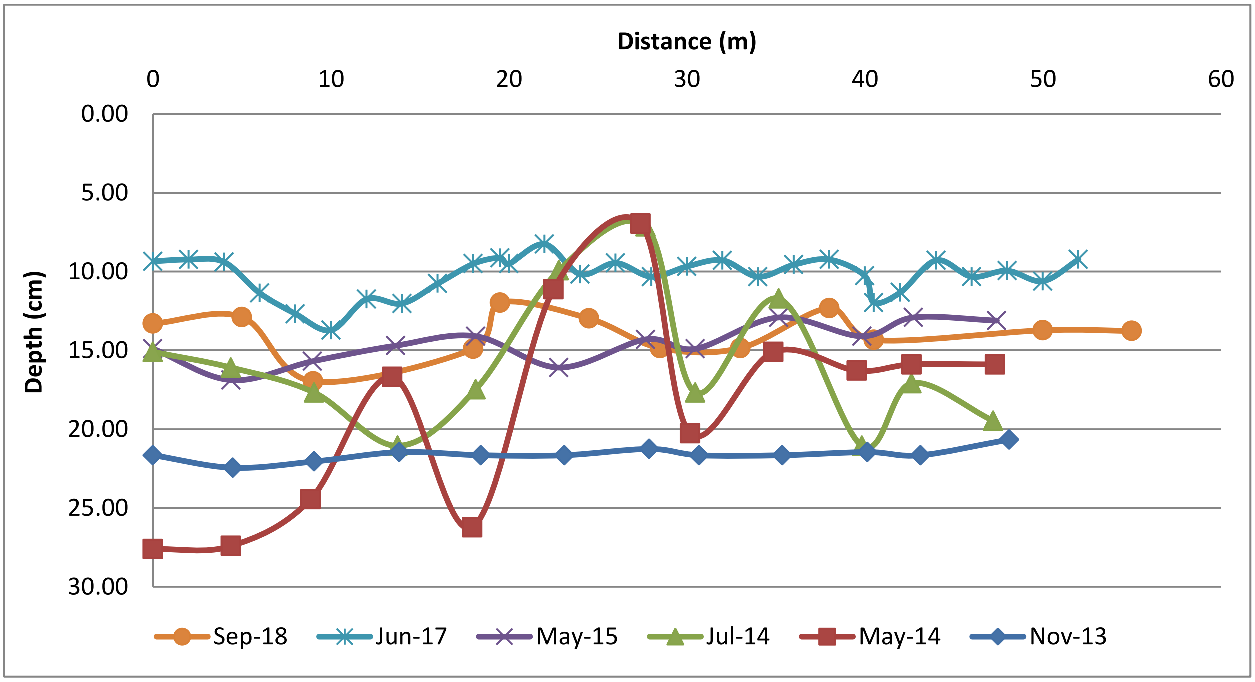

Figure 5-9: GPR data for VIF segment

5.8.2 JETT Network (SMCI)

The same difficulty with sand backfill was encountered in the SMCI loop. The conduit has moved considerably and progressive analysis has shown the same tendency of movement toward the surface. SMCI is a much shallower application with a lower volume of sand as backfill, so the magnitude of movement was noticeably smaller. The worst scenario was observed 14 m along the path in a place where the entire area around the trench is suffering with differential settlement, which is unlikely to be caused by the trench but is naturally affecting it. Additionally, a certain wave pattern can be distinguished in the way the conduit progresses along the trench path. Considering the same pattern was observed in the first analysis in 2014, it is likely to be associated to uneven pouring of backfilling material during the application. Figure 5-10 displays GPR analysis performed throughout different years in the SMCI loop.

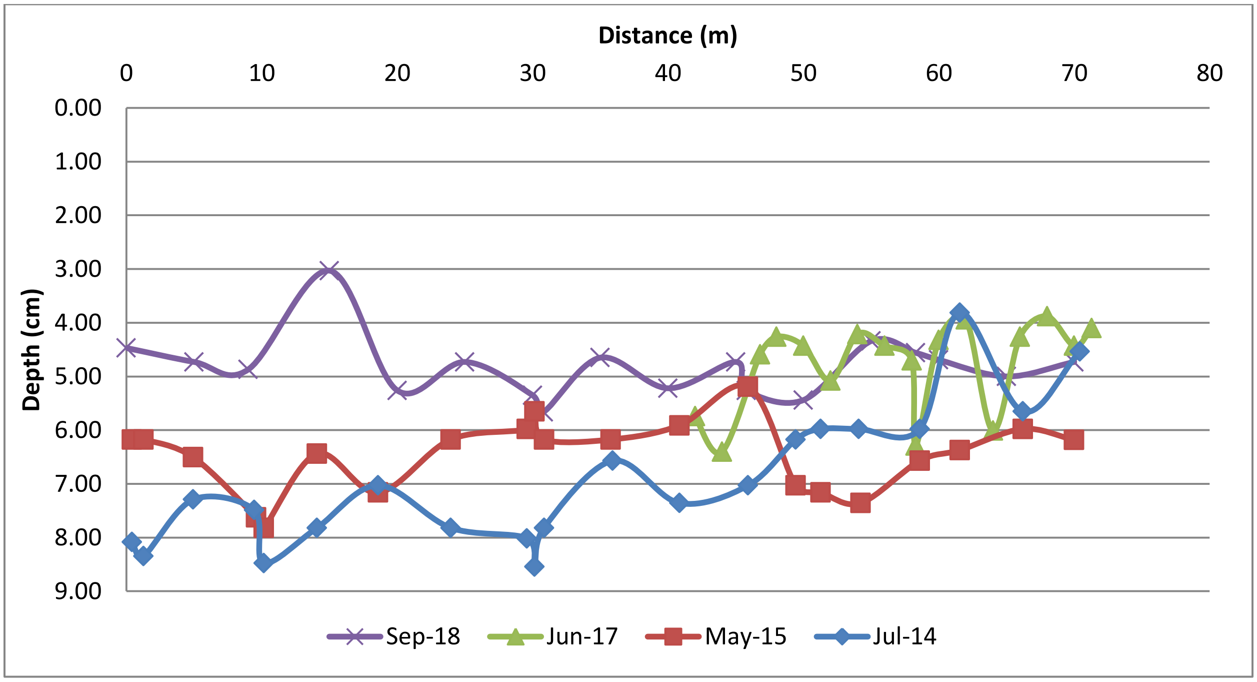

Figure 5-10: GPR data for SMCI segment

5.8.3 University Applications (multiple backfilling)

Every novel material proposed by the University was able to secure the conduit in place with a fair amount of certainty. Grout materials are fluid and strong enough to flow below the conduit and create a protection around it. Such protection reduces the likelihood of movement inside the trench, as well as eliminates the possibility of differential settlement, unless the grout fails completely. Little movement was observed in the grout + sealant sections, which is associated to the aforementioned heaving of the material and possible cracks generated from such displacement. Nonetheless, the magnitude of movement for each path analyzed is substantially lower than VIF and SMCI applications. Aggregate + emulsion also presented a reliable form of securing the cable down the trench; emulsion fills in the voids in the uniformly distributed aggregate and provides bonding properties to the material. As long as the rupture is concluded, bitumen will harden and grant a similar level of protection as observed in grout. Figures 5-11 to 5-13 present GPR analysis for consecutive years in segments A-G and H-J.

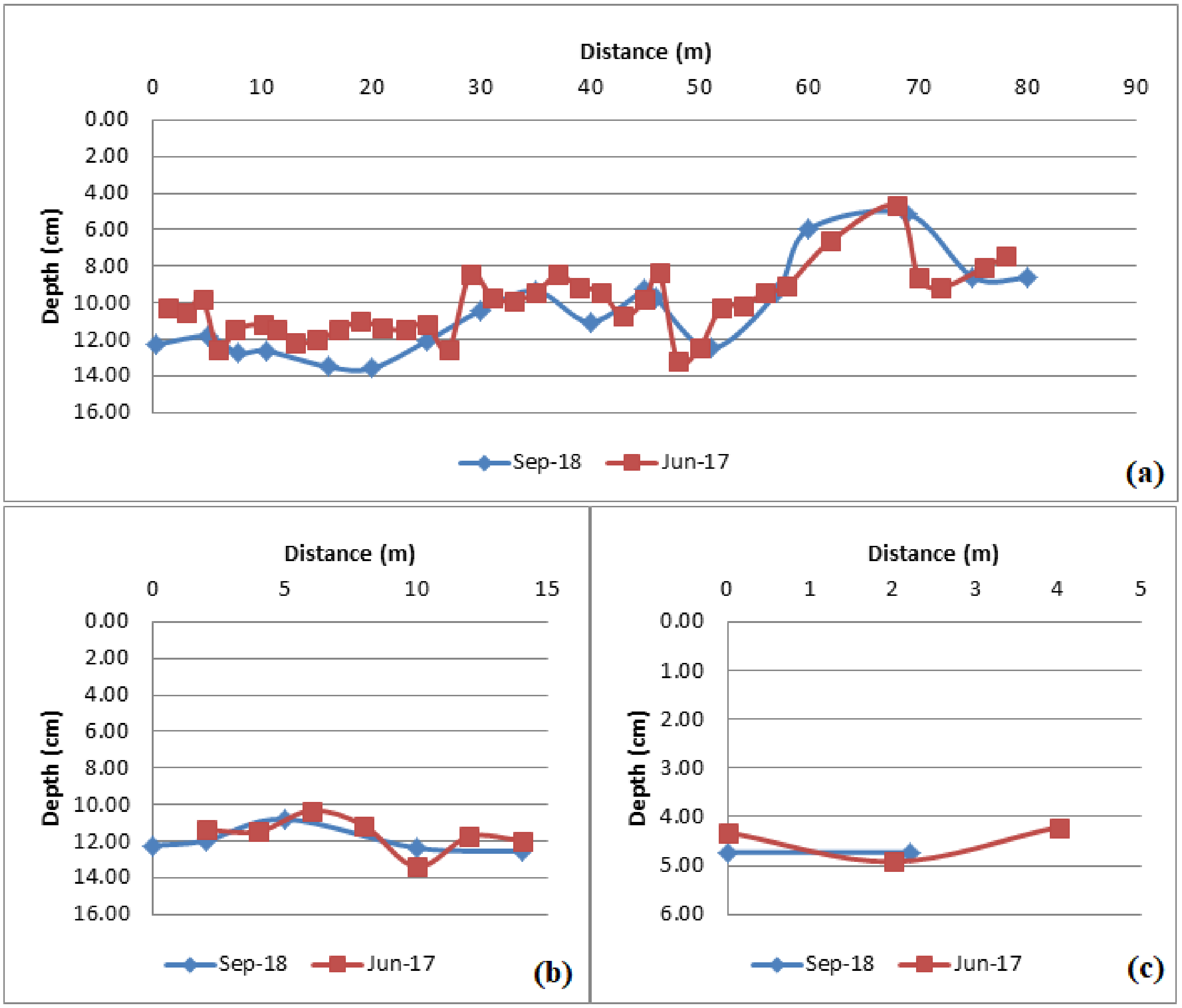

Figure 5-11: GPR data for grout + cold mix + sealant segments. (a) A-D. (b) D-E. (c) E-F

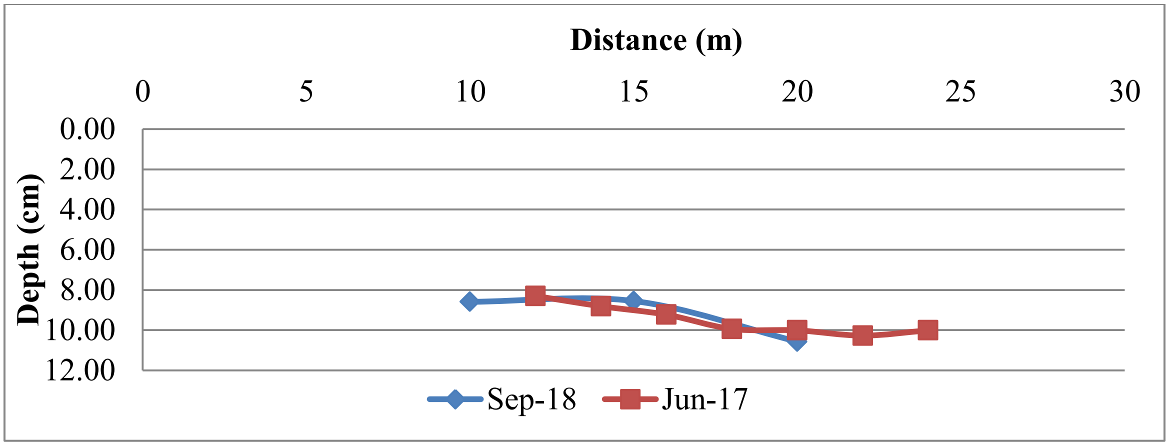

Figure 5-12: GPR data for aggregate + emulsion segment (I-J)

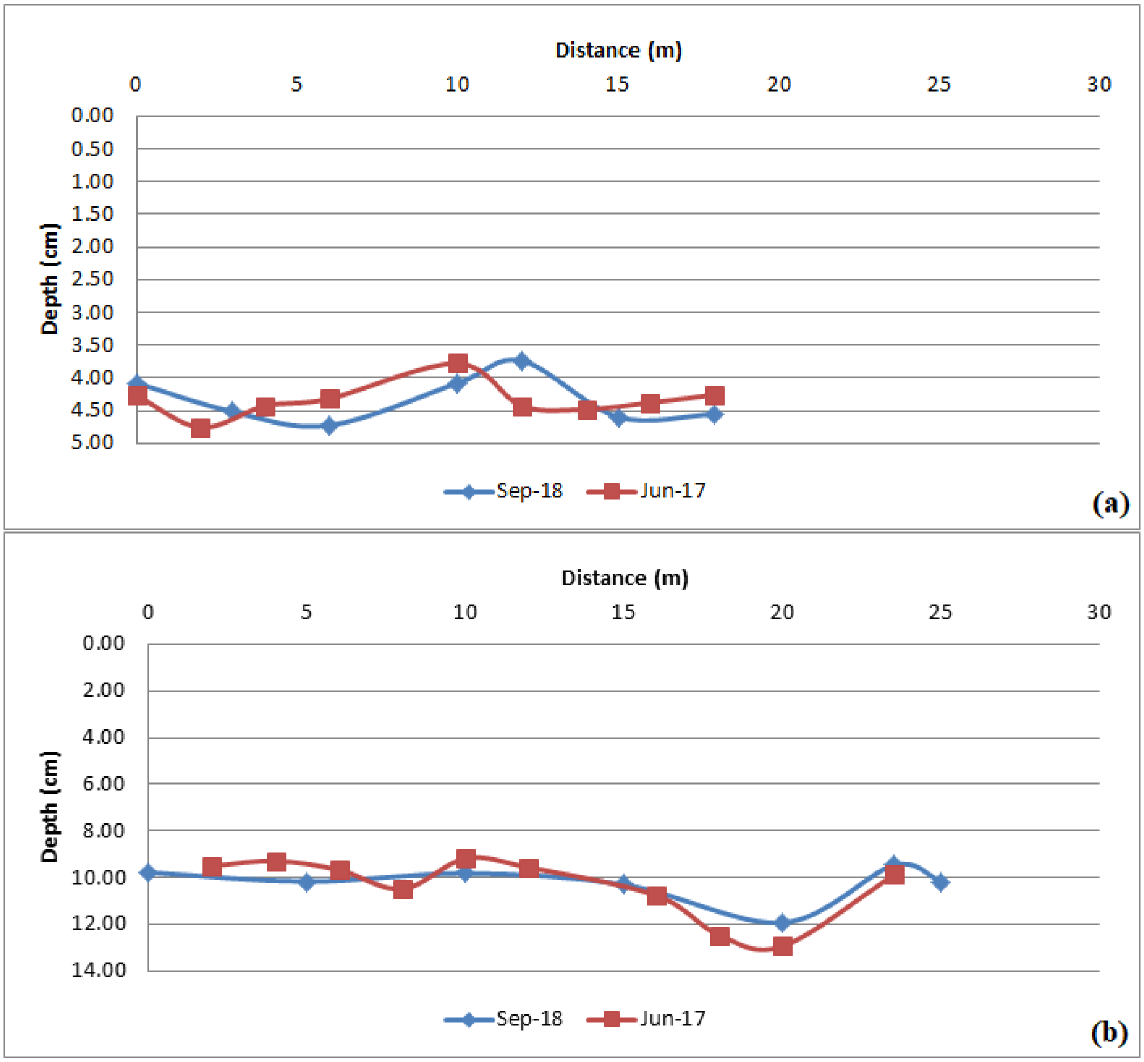

Figure 5-13: GPR data for grout + sealant segment. (a) F-G. (b) H-I

5.9 Cored Sections

GPR analysis of cored sections presented an interesting detail of radar data collection. Because the entire depth is filled with one single material, it was extremely easy to differentiate this specific section from the surrounding area as seen in Figure 5-14. Such observation clarifies GPR ability to provide more accurate and reliable data when a single material is evaluated, a scenario in which not only dielectric properties can be estimated with more accuracy, but also interference is reduced as a result of the signal traveling without interruptions.

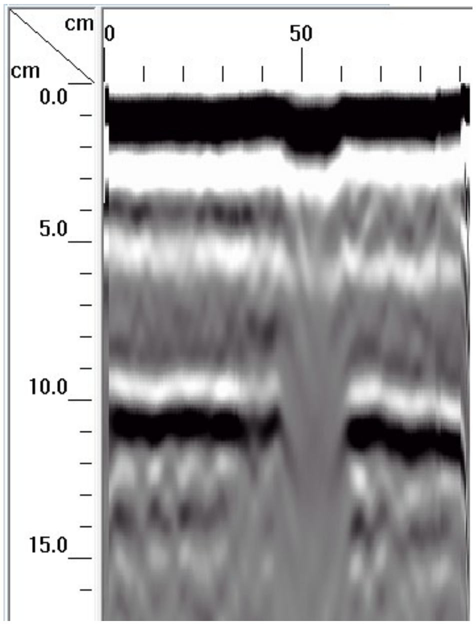

Figure 5-14: Data collection of cored sample

5.10 Conclusions

Conclusions obtained from this study can be summarized as follows:

1. As proved in previous literatures, sand is a poor backfilling material for micro-trenching because it is unable to secure the conduit and can be easily washed away.
2. The composite backfill of grout + cold mix + sealant proved to be extremely effective for micro-trenching applications, as it provides structural safety for the conduit, fills the gaps inside the trench, properly bond with the existing structure, and prevents the ingression of water.
3. Considerable care should be taken with grout + sealant backfill due to the poor bonding between cementitious and bituminous materials. Additives like foam can be added to

grout mixes to close the compressive strength gap and reduce differential displacement, as well as proper application of sealant is paramount to avoid cracking and later water ingress.

4. Emulsion is able to provide structural security for the conduit; however, not only are application procedures not reliable, but too many pavement distresses developed throughout service life. Material consistency is a major concern for this technique. There are no fines presented in the mix and the exposed material at the top of the trench breaks faster, creating a layer of bitumen and sealing the trench. Such process prevents the deeper material in the trench to break, making it harder to estimate the minimum time required to reopen the site to traffic.
5. GPR accuracy improves when the signal travels through a single material of known properties.

5.11 Future study and recommendations

Pilot testing areas such as the one presented in this research are extremely relevant, especially to gain better understanding of innovative techniques such as micro-trenching. A remarkably high amount of materials are available in industry for different applications and the ability to extensively test such materials prior to real project applications is vital to expand and improve construction techniques. State-of-the-art materials like engineered cementitious composite (EEC) and water reactive asphalt mixes are prominent solutions to micro-trenching that can be tested in the laboratory and applied in the pilot area in future studies.

6 Summary and Conclusions

6.1 Summary

Broadband networking is quickly expanding globally, resulting in the increasing importance of infrastructure for the telecommunications industry. Fiber optic cables have proven to be a reliable technology to support the enhanced demand; however, techniques to install fiber optic networks still lack effectiveness. Despite the fact that micro-trenching presents a fast-paced method with minimal disturbance to existing structures, there are challenges that remain unsolved when the performance of backfilling materials is taken into consideration.

The focus of this study is to assess material performance for application in micro-trenching backfilling procedures in cold regions. For this purpose, grout mixes were submitted to freezing thawing cycles and tested for compressive strength. Results were compared before and after conditioning and a cost comparison was drawn based on each individual component of the mixes. Measurements of the samples' dimensions and failure mechanisms provided additional information on differences in performance. Additionally, visual observations and GPR analysis were conducted in a pilot test area in Edmonton, Alberta. This study gives continuity to previous studies conducted in the same area with the objective of evaluating short and long-term performance of different backfilling materials and micro-trenching configurations. Pavement distresses were observed and their relationship with the trenches investigated. Data collected by GPR was compared to data from previous years to track conduits inside the trenches and determine downwards and upwards movements. Recommendations were then presented for future considerations.

6.2 Conclusions

The analysis of laboratory tests and field performance of micro-trenching is extremely important for industry applications, providing the broader understanding of a proposed solution through a reliable complimentary study. Test results to evaluate foam and regular grout resistance to freezing/thawing cycles revealed a substantial contrast between both materials, while visual observations and GPR data collection of the pilot testing area exposed differences in performance for distinct materials and configurations. The conclusions obtained are summarized as follows:

1. The existence of air pockets inside foam grout samples allows water ingress and expansion throughout conditioning, a process that not only mitigates crack propagation due to water expansion, but also increases the specimen's density and consequent compressive strength. Deterioration was only observed after 14 and 28 days of curing in the very last conditioning cycle. In contrast, for regular grout, any water present inside the mix during conditioning is extremely harmful to the material, as there is no room for expansion and any movement will cause the material to crack from inside out. The development of the first crack creates an opening for water ingress that will make deterioration exponentially faster as conditioning progress. Specimens cured for 3 days deteriorated after the first freezing cycle, and the longest the material can resist is 7 cycles of conditioning.
2. Observations of the failure mechanisms for foam and regular grout before and after freezing/thawing cycles also revealed interesting findings. Regular grout specimens submitted to freezing temperatures before curing was complete were unable to form a proper bond between cement crystals and present the typical clean and plain cut of cementitious materials. The end result was a scattered surface, very similar to compacted aggregates. For foam grout, the same air voids inside the mix are able to prevent crack propagation to a certain degree, as a new crack needs to develop every time the progression is broken by an air pocket. This behavior not only makes it difficult to identify a clear crack pattern, but also delays complete failure of the material.
3. When immediate freezing is considered, foam grout samples lost their entire structure and collapsed. The material requires a minimum setting time to properly bond before being subjected to freezing conditions. Regular grout, in contrast, still exhibited the capacity of setting and gained a reasonable amount of strength, even though the magnitudes obtained were considerably lower than samples that were cured at room temperature.
4. An appreciable decrease in material cost was calculated for foam grout. The addition of foam in any quantity increases the total volume of the mix, reducing the quantity takeoffs of cement and water. The volume of foaming agent is insignificant when compared to the other materials in the mix. However, care should be taken while adding foam, once any decrease in density will result in a loss in compressive strength. Project requirements

must be used to identify the maximum savings that can be obtained in material cost while complying with strength minimum requirements. In this study, an addition of 1.64% of foam in mass resulted in an average compressive strength of 4 MPa, while saving more than 50% in cement cost.

5. Field analysis demonstrated that the usual practice of using sand as a backfilling material for micro-trenching is the main issue for the current state of the technology. Aside from the fact that sand can be easily washed away, it did not secure the conduit in place and considerable movement was observed in both upward and downward direction throughout the service life. VIF and SMCI technologies exposed maximum net conduit movement of 14.31 cm and 4.79 cm respectively. Additionally, conduit integrity is at a high risk, considering that severe bending of the conduit was encountered in certain sections of the micro-trenching installation path.
6. Taking into consideration all the auxiliary proposals presented by the University of Alberta, the following observations were made:
    a. The composite backfill of grout, cold mix and sealant proved to be the most efficient. Grout's flowability is extremely effective in filling gaps and securing the cable down the trench, cold mix bonds very well with the existing pavement layer as long as tack coat and compaction are executed properly, and the bituminous sealant eliminates any possibility of water ingress.
    b. The combination of grout and sealant presented an interesting solution; however, a lot of care should be taken with the interface between the backfilling material and the existing structure. The bonding of bituminous and cementitious materials is rather poor, causing the interface to be highly susceptible to cracks.
    c. For fine aggregates and emulsion, despite the fact that emulsion is able to provide structural security for the conduit, too many pavement distresses developed throughout the service life. Due to inconsistent application procedures, some sections of the path were noted to have excess of emulsion, whereas settlement developed in others for lack of material. Additionally, the absence of fines in the mix and the large depth/width ratio allows for the exposed material in the top of the trench to break faster, creating a layer of bitumen and sealing the trench. Such processes prevents the material down the trench to break, making it harder to

estimate the minimum time required to reopen the site to traffic and creating a major concern related to the consistency of the material.

6.3 Future Research

Construction is an industry the exhibits a constant desire to improve and develop new and more reliable products. Innovative products are readily available with specific applications, addressing particular project needs in distinctive areas. Two examples of such materials are engineered cementitious composites (EEC), grout-like products incorporating a large amount of fibers that grant flexural strength properties to the material, and cold mixes that require the addition of water to achieve workability, solving to a certain degree the problem of applications in rainy seasons and simultaneously facilitating work execution. The possibility of comparison of results from laboratory testing and field applications is a remarkable advantage to the industry, as it encompasses particular challenges faced by backfilling materials throughout the service life. The approaches demonstrated in this work can be used to assess novel materials and enhance the reliability of the micro-trenching technique for future projects.

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Appendix A

In an effort to give continuation to material testing in the laboratory, novel products were tested as possible solutions for micro-trenching backfilling. Three of them deserve especial credits for the successful result obtained:

- Polymer modified asphalt pavement repair mastic (PMA);
- Engineered cementitious composite (ECC);
- Water activated cold mix asphalt (CMA).

Cementitious materials were tested for resistance to freeze/thaw cycles using the same methodology as presented in previous papers on this research, as well as, flexural strength according to ASTM C78: Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading). All materials were tested for resistance to permanent deformation according to AASHTO T 324: Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures. Test results are presented as follows:

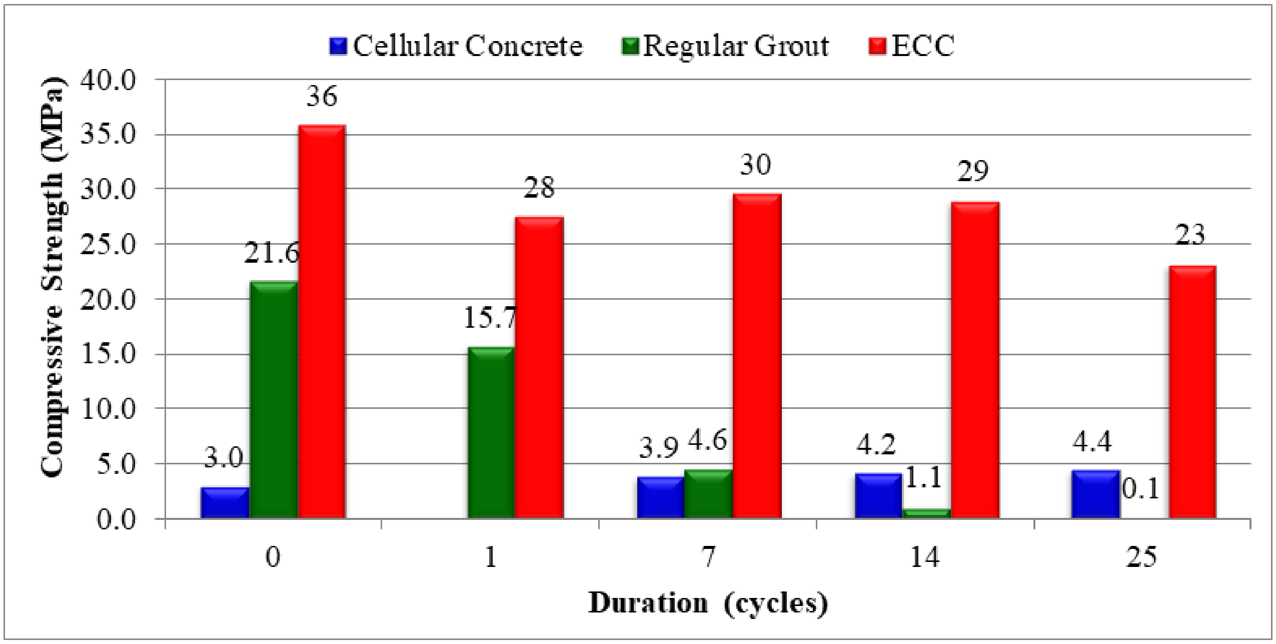


Figure: Compressive strength comparison

TABEL: Flexural strength test results

	Flexural Strength (MPa)
Regular Grout	2.4
Engineered Cementitious Composite (ECC)	6.4

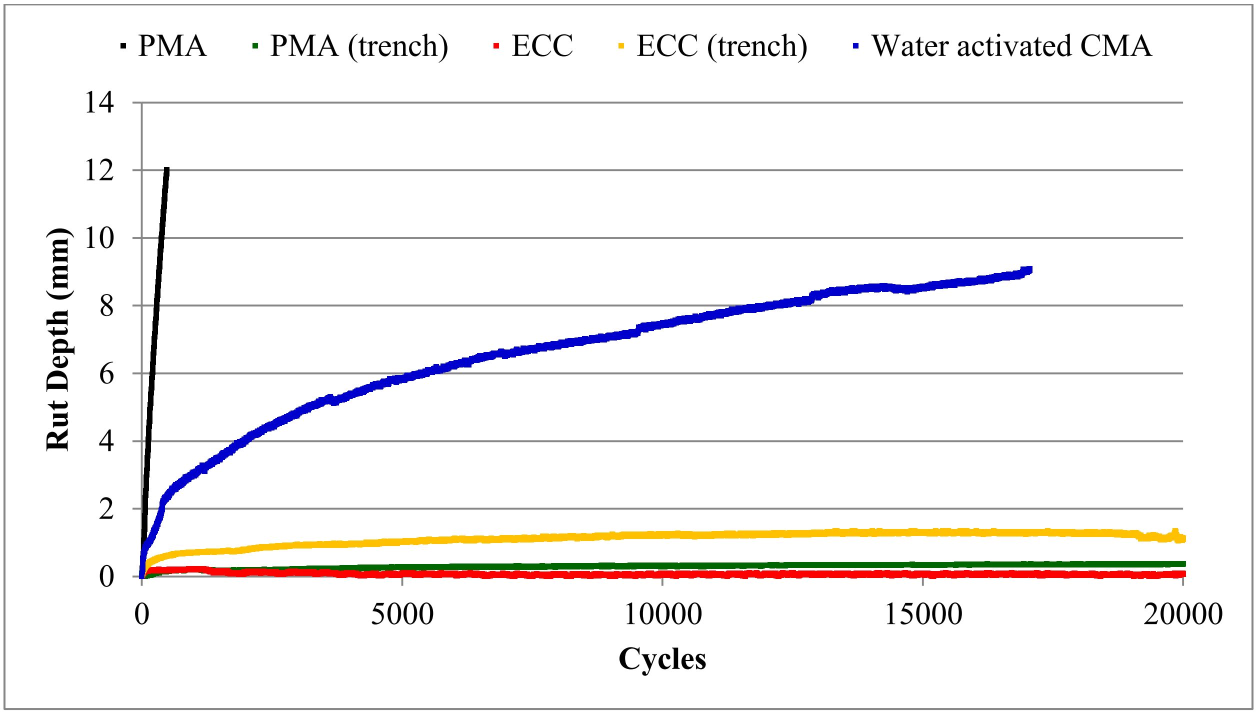


Figure: Test results for wheel tracker

Pictures of the tests are provided as follows:

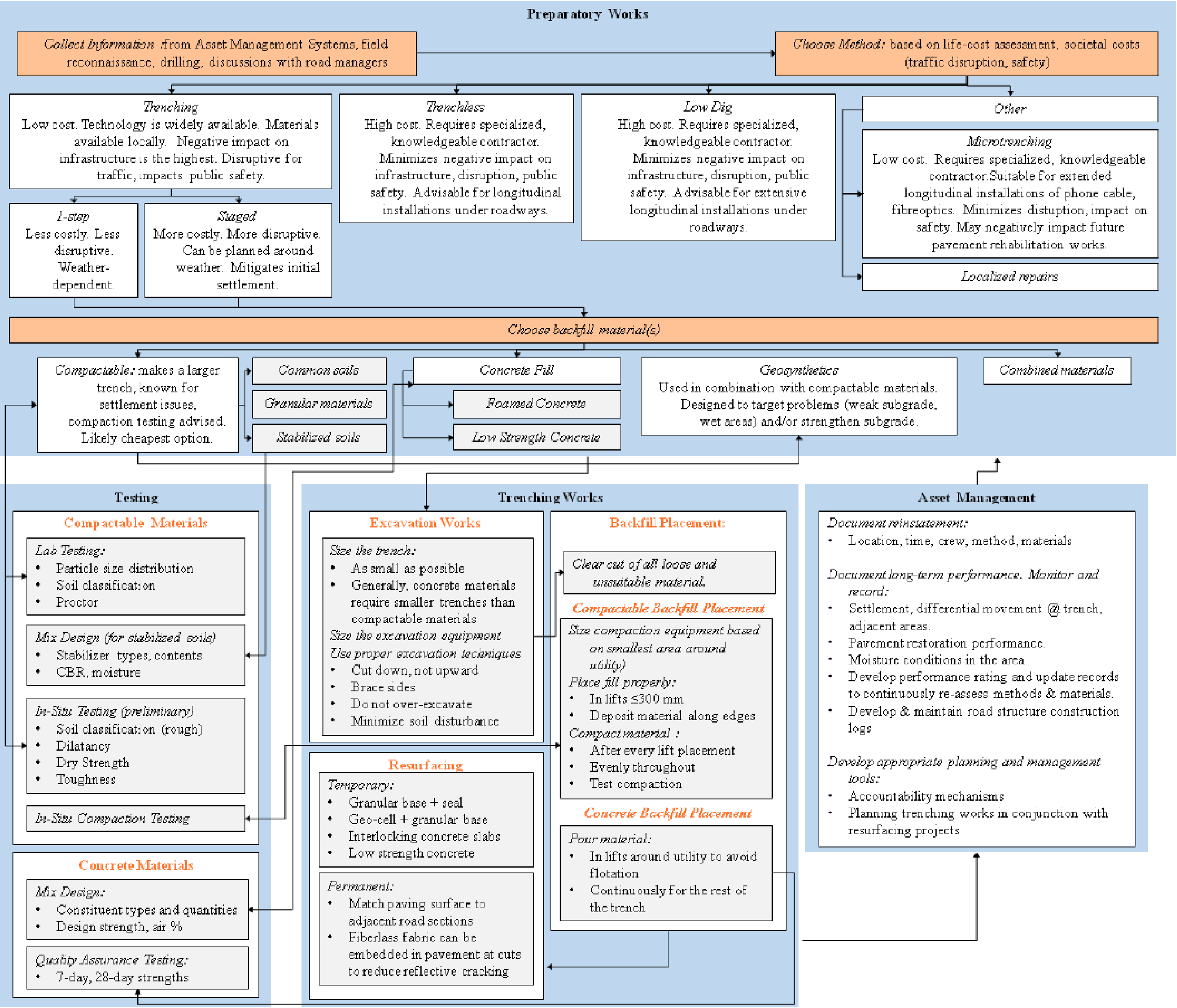
Figure: Details of ECC after compressive strength (Left) and flexural strength (right) tests.

Figure: Details of PMA and PMA (trench) before and after wheel tracker test

Figure: Details of ECC and ECC (trench) after wheel tracker test

Figure: Details of water activated CMA before wheel tracker test

Appendix B



Preparatory Works

Collect information from Asset Management Systems, field reconnaissance, drilling, discussions with road managers

Choose Method: based on life-cost assessment, societal costs (traffic disruption, safety)

Trenching
Low cost. Technology is widely available. Materials available locally. Negative impact on infrastructure is the highest. Disruptive for traffic, impacts public safety.

1-step
Less costly. Less disruptive. Weather-dependent.

Staged
More costly. More disruptive. Can be planned around weather. Mitigates initial settlement.

Trenchless
High cost. Requires specialized, knowledgeable contractor. Minimizes negative impact on infrastructure, disruption, public safety. Advisable for longitudinal installations under roadways.

Low Dig
High cost. Requires specialized, knowledgeable contractor. Minimizes negative impact on infrastructure, disruption, public safety. Advisable for extensive longitudinal installations under roadways.

Other

Microtrenching
Low cost. Requires specialized, knowledgeable contractor. Suitable for extended longitudinal installations of phone cable, fibreoptics. Minimizes distuption, impact on safety. May negatively impact future pavement rehabilitation works.

Localized repairs

Choose backfill material(s)

Compactable: makes a larger trench, known for settlement issues, compaction testing advised. Likely cheapest option.

Common soils

Granular materials

Stabilized soils

Concrete Fill

Foamed Concrete

Low Strength Concrete

Geosynthetics
Used in combination with compactable materials. Designed to target problems (weak subgrade, wet areas) and/or strengthen subgrade.

Combined materials

Testing

Compactable Materials

Lab Testing:
- Particle size distribution
- Soil classification
- Proctor

Mix Design (for stabilized soils)
- Stabilizer types, contents
- CBR, moisture

In-Situ Testing (preliminary)
- Soil classification (rough)
- Dilatancy
- Dry Strength
- Toughness

In-Situ Compaction Testing

Concrete Materials

Mix Design:
- Constituent types and quantities
- Design strength, air %

Quality Assurance Testing:
- 7-day, 28-day strengths

Trenching Works

Excavation Works

Size the trench:
- As small as possible
- Generally, concrete materials require smaller trenches than compactable materials

Size the excavation equipment

Use proper excavation techniques
- Cut down, not upward
- Brace sides
- Do not over-excavate
- Minimize soil disturbance

Resurfacing

Temporary:
- Granular base + seal
- Geo-cell + granular base
- Interlocking concrete slabs
- Low strength concrete

Permanent:
- Match paving surface to adjacent road sections
- Fiberlass fabric can be embedded in pavement at cuts to reduce reflective cracking

Backfill Placement:

Clear cut of all loose and unsuitable material.

Compactable Backfill Placement

Size compaction equipment based on smallest area around utility)
Place fill properly:
- In lifts ≤300 mm
- Deposit material along edges

Compact material :
- After every lift placement
- Evenly throughout
- Test compaction

Concrete Backfill Placement

Pour material:
- In lifts around utility to avoid flotation
- Continuously for the rest of the trench

Asset Management

Document reinstatement:
- Location, time, crew, method, materials

Document long-term performance. Monitor and record:
- Settlement, differential movement @ trench, adjacent areas.
- Pavement restoration performance
- Moisture conditions in the area
- Develop performance rating and update records to continuously re-assess methods & materials.
- Develop & maintain road structure construction logs

Develop appropriate planning and management tools:
- Accountability mechanisms
- Planning trenching works in conjunction with resurfacing projects