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Laboratory Testing of High Performance Repair Materials for Pavements and Bridge Decks

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LABORATORY TESTING OF HIGH PERFORMANCE REPAIR MATERIALS FOR PAVEMENTS AND BRIDGE DECKS

KAMRAN AMINI

ABSTRACT

Because of numerous freezing and thawing cycles happening during the year in the state of Ohio, pavement partial-depth patching has become a common maintenance activity in this state. The Ohio Department of Transportation (ODOT) has a need for durable, more permanent high performing pavement and bridge deck materials that allow for a faster repair and for user safety. However, new or proprietary products are difficult to specify unless incorporated into a construction project for research purposes or procurement of the product complies with the ODOT's direct purchasing requirements.

This research project was conducted in three main phases, literature review and selecting the proper materials, field patching and inspection of the materials, and laboratory testing of the materials to compare the results to the field inspections. All these phases were conducted in order to specify for use in future ODOT construction, based on the field and laboratory performances of the products. As the last phase of this research project, this thesis investigates the properties and performance of the selected products used for partial-depth repair of concrete pavement in a laboratory. The materials were tested for freeze-thaw, modulus of elasticity, strength, shrinkage, ultrasonic pulse velocity, mass change, and scaling damage to quantify their characteristics relative to those products known to work well. The objective of this study was to document the investigation of the lab testing of selected repair materials for partial-depth repair. The

investigation determined the acceptable laboratory tests for comparative analysis of existing repair materials. Eventually, the investigated materials were ranked based on their overall performance considering economic aspect and their laboratory and field performances.

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ACRONYMS

AASHTO	American Association of State and Highway Transportation Officials
ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
ATSSA	American Traffic Safety Service Association,
DOT	Department of Transportation
ERDC	Engineer Research Development Center
HPRM	High Performance Repair Material
MSDS	Material Safety Data Sheet
NTPEP	National Transportation Product Evaluation Program
ODOT	Ohio Department of Transportation
OPCC	Ordinary Portland Cement Concrete
RDM	Relative Dynamic Modulus
SSD	Saturated Surface Dry

CHAPTER I

INTRODUCTION AND RESEARCH OBJECTIVES

Introduction

Pavements and bridges are essential elements of any transportation system. Any deficiency in the performance of these elements reduces the mobility of the system and as a result, road users will experience high expenses, increased commute time, and unsafe roads. Moreover, the overall economy will suffer. Specifically, the United States has a significant investment every year in construction, maintenance, preservation, repair, and rehabilitation of the Nation's lifeline systems consisting of concrete pavements and bridge decks (Delatte et al., 2001), which are deteriorating caused by environmental attack, heavy use, and age. The accumulated investment in the roadway pavements and bridge decks is in the trillions of dollars (Tayabji, Van Dam, & Smith, 2009). This investment needs to be protected and managed efficiently.

Therefore, as an effort to improve mobility on the roads, while holding down expenses, a need for durable and more permanent high performing patching materials can be specified. However, the evolution of current specifications from customary scheme, such as prescriptive specifications, to performance-based specifications makes it difficult to employ new materials. Many of the current available materials used for the repair purposes have been used for several decades. However, producing a material that performs better than the current in service materials is still a subject of competition for companies and developers. On the other hand, newer materials are difficult to specify unless incorporated into a construction project for research purposes or procurement of the product complies with the ODOT's direct purchasing requirements. As a result, this may create a situation in which the desired product is precluded from use.

When high-performance repair materials (HPRM) are applied as a patching material on a pavement and/or bridge deck, they provide a long service life with minimal maintenance by exceeding the properties and constructability of normal concrete (Zia, Ahmad, & Leming, 1991). Producing and handling of HPRMs may require specialized mixing, placing, and curing methods. These materials have been primarily used to repair and rehabilitate pavements, tunnels, and bridges for their strength, durability, and high modulus of elasticity. However, different signs of damage, such as cracks can be developed due to a variety of factors, like overloading, chemical attack, drying shrinkage (Alhozaimy & Hussain, 2012)**,** freeze-thaw cycles, differential settlement, weathering (Valcuende, Parra, & Marco, 2012), and/or a combination of these factors. Moreover, adequate repair of this deteriorated pavement/bridge deck is harder than asphalt pavement in case of degradation or damage (Choi, Park, & Jung, 2011). Therefore, better knowledge of durability and speedy repair techniques would be a further advantage in supporting the use of concrete pavements and bridge decks, especially for those located in severe environmental circumstances (Cement Concrete & Aggregates Australia, n.d.).

Research Context

Repair is a complicated issue. The general principle is to repair concrete and asphalt with cementitious materials and hot mix/cold patch materials, respectively. However, some materials are difficult to supply in small quantities. Asphalt repair materials may be difficult to compact effectively in small patches. In addition, rapid hardening cementitious materials are preferred over traditional concrete to reduce traffic interruptions. Furthermore, durable repairs demand different material properties from initial construction. For example, bond strength and dimensional stability, such as limits on shrinkage or expansion, may be much more significant than compressive strength. High early strength cementitious materials may also have high stiffness (modulus of elasticity), which can lead to stress concentrations and early patch failure.

Installation procedures also have a significant effect on performance. Removal of existing distressed material must be carried out carefully to prevent extra damage to the remaining pavement or bridge deck. Curing of cementitious materials and proper compaction of asphalt materials may be difficult to carry out on a small scale, but critical to long-term performance of repairs.

Two primary resources to this study are the National Transportation Product Evaluation Program (NTPEP) (NTPEP, 2008), and the U.S. Army Engineer Research and Development Center (ERDC) (Priddy, 2011). NTPEP has four reports documenting two year test results for Rapid Set Concrete Patching Materials published, and the ERDC, has recently published two reports evaluating materials for repairing concrete airport pavements, using both laboratory and field testing with a focus on commercially available repair materials and two reports on asphalt patching on airfield and highway pavements.

Objectives

The main objective of this thesis is to conduct a laboratory study to address the potential repair materials to make repairs at severe climate conditions in portland cement concrete pavements and bridge decks. It attempts to determine more durable and permanent high performance pavement and bridge deck patching materials that can be specified for use in future bridge and pavement patching construction projects. A combination of an accelerated pavement repair with more durable and longer lasting materials will also help with worker and user safety of the bridge patches, along with lowering future repair and construction costs.

In order to accomplish the main objective, the project has the following sub-objectives:

- Determination of acceptable laboratory tests for comparative analysis of existing repair materials.
- Organize a guideline for a selection process of repair materials to be used for partial depth repair.
- Document the lab testing of selected repair materials for partial-depth repair.
- Compare and investigate the repair materials tested and their results based on the lab and field findings.

Scope

This study focuses on a lab program to evaluate the performance of the repair materials bonded to concrete to determine whether the bond degrades under freeze-thaw cycles. In addition, the tests used by the ERDC Repair Materials Certification Program[1] were also applied to evaluate the specification of the high performance materials (HPRMs) in this

[1] The Repair Materials Certification Program, headed by Pete Bly, of ERDC, is an ongoing program that tests or recertifies three to six proprietary products per year.

study. After performing a general preview regarding pavement and bridge deck repair projects and HPRMs, data and data analysis for all measurable characteristics is provided.

Benefits and Potential Application of Research Results

Partial depth patching is a growing concern in cold climate regions, where aging of pavements exhibit increased distresses. Thus, this research was conducted in order to improve the reliability of the products that are used for partial depth patching of these distresses. The benefits of this research project are:

1. Anticipated cost savings by reducing the repairs.

2. Improved durability and increased longevity of ODOT's roads.

3. More sustainable/successful pavement/bridge deck repair operation by ODOT personnel.

Efficiency, including time, effort, and cost- will be optimized by maximizing the longevity of a pavement/bridge deck. It improves the performance of the transportation system and as a result, advances the mobility.

Organization of the Report

This thesis is organized into seven chapters. Chapter 2 provides the background and literature review. Review of the technical literature aided in developing the testing plan and helped on providing the list of the products that were investigated. Chapter 3 describes the selected materials in detail. Chapter 4 reviews the test methods and testing procedures that were applied in this study. Chapter 5 presents the test results and describes the analysis of the test results and the implications associated with the findings. Along with presentation of results, discussions are provided on the findings from the laboratory testing program.

On the basis of research conducted throughout this project, Chapter 6 presents the field findings and comparison of the investigated materials based on their performance. Finally, Chapter 7 summarizes the study and lists the key conclusions.

The raw results of the conducted tests are attached as appendix A through Appendix F.

CHAPTER II

BACKGROUND AND LITERATURE REVIEW

This chapter addresses the repair process, factors that govern a good concrete pavement repair material, partial depth repair, and common causes of failure for partial depth patching. In addition, it reviews classes of repair materials, factors affecting the selection of repair materials, and the selected repair materials for this project.

The application of quick-setting materials for repairing of concrete pavements and bridge decks is not a new approach. The development of techniques to assess the wide spectrum of materials, which have been used by different state departments of transportations (DOTs) has been a subject of many researches for over two decades.

The U.S. Army Engineer Research and the Development Center and The National Transportation Product Evaluation Program have both carried out investigations on concrete pavement and bridge deck repair materials to assess their suitability for field applications.

Under agreement with The American Traffic Safety Surfaces Association (ATSSA), NTPEP Project Panel on quick-setting patching materials has two industry representatives.

This confirms the industry concerns in the testing and evaluation of products and assures that technical knowledge and experience are reflected in the testing of the materials and devices that are commonly used by the AASHTO member departments (NTPEP, 2007, 2008)

ERDC reports about many available commercial-off-the-shelf products that can be used for small surface repairs in portland cement concrete pavements. Standard tests have been performed in laboratory to verify the material specifications and to evaluate the material suitability for field applications. Field testing has also been conducted and evaluated under controlled conditions.

The results confirm that the design engineer cannot be assured that the material will meet performance expectations, unless the properties of the material have been recently verified. To overcome the problems of repackaging and reformulation, the American Association of State Highway and Transportation Officials (AASHTO) recommends retesting the products every five years (Priddy, 2011).

Repair of Concrete Material (Pavement and Bridge deck)

In order to achieve success in a repair project, it is essential to primarily perform a detailed and broad evaluation (Delatte, 2009). The purpose of the main assessment is shown in Figure 1. In general, it is necessary to understand the difference between the defects in concrete and defects caused by corrosion in reinforcement. Reinforcement corrosion in concrete can be a major issue and it was the main reason of the damages in this project. Normally, high pH level of concrete (more than 12.5) causes formation of an inactive layer of ferric oxide around the reinforcement (TRC E-C107, 2006). Therefore, the reinforcement starts to rust, which expands the steel. This expansion of steel causes the concrete to spall or flake off, which exposes more steel. Typically, chloride penetration and carbonation are two major causes of corrosion in the reinforced concrete. As can be seen in Figure 2 both causes of corrosion end similarly. Moreover, common causes of defects according to En 1504-9 are shown in Figure 3.

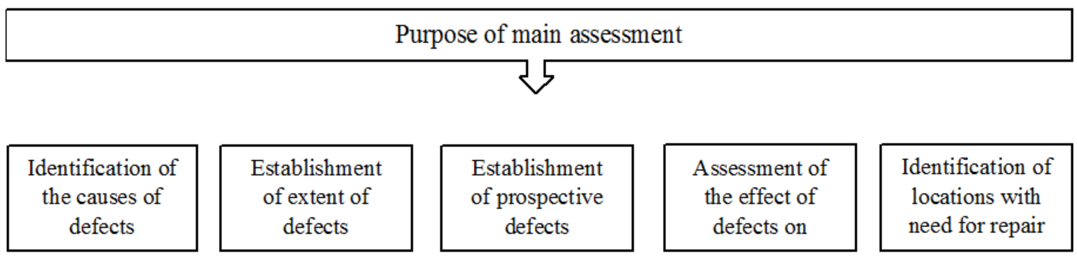


Figure 1. Purpose of main assessment according to EN 1504-9 (EN 1504-9, 2008)

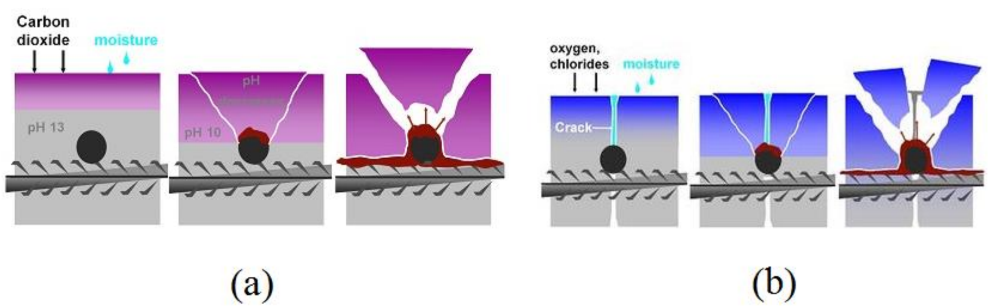


Figure 2. (a) Process of chloride penetration, (b) Process of carbonation (Pirro, 2012)

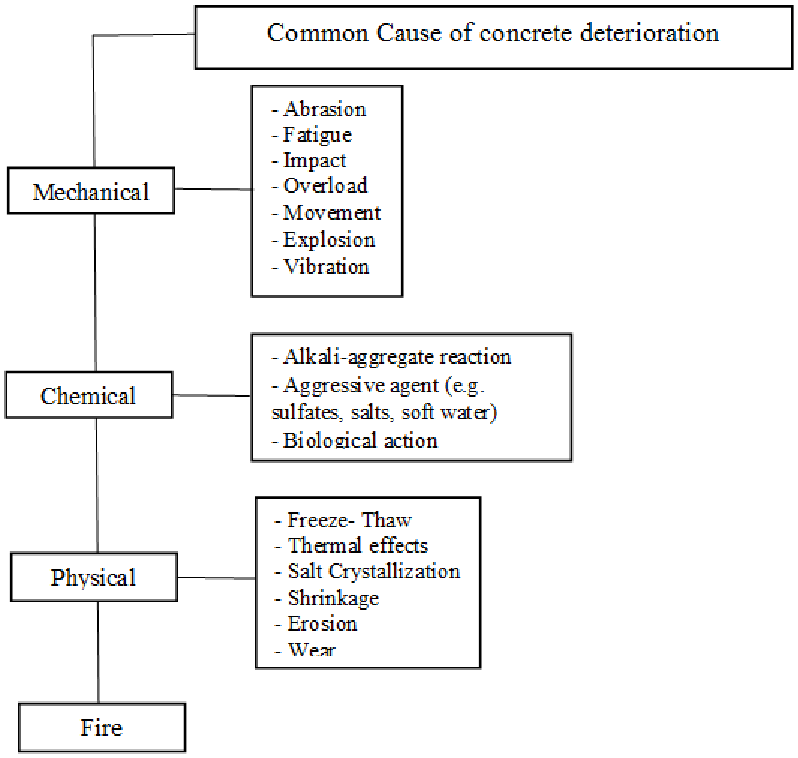


Figure 3. Common causes of defects according to EN 1504-9 (EN 1504-9, 2008)

There is an increasing need to develop better repair techniques that guarantee the success of the rehabilitation and keep the number of repeat interventions to a minimum. In this case, the key parameter is to design a repair system that addresses the causes of failure in a concrete material. It is convenient to recall the primary causes such as errors in the phases of design or construction, structural loads, extraordinary actions, abrasion and erosion, and excessive deterioration due to chemical attack or aggressive environmental condition, by which a concrete system may need to be repaired (Delatte, 2009). The addition of excessive amount of water in concrete mixtures, low quality concrete, inadequate joints, and construction defects are some general instances that introduce errors in the phases of design or construction. On the other hand, regarding to the chemical and physical causes of concrete deterioration, the most common causes are alkali-aggregate reaction, sulfate attack, carbonation and freezing-thawing cycles (Muñoz, 2012).

Many references such as “Concrete Pavement Design, Construction, and Performance” (Delatte, 2007) and “Repair and Protection of Concrete Structures” (Barnes, 1995), provide a broad summary of the complications and solutions to the damaged concrete (Barnes, 1995). In addition, they offer an overview to different types of repair materials currently used and their general specifications. For that purpose, the American Concrete Pavement Association (ACPA) (ACPA, 2004) recommends considering the elastic modulus of the material, material strength, bond strength, resistance of the material to freezing and thawing cycles, and shrinkage as key parameters to choose a repair material. The research conducted by A. Sommerville (Sommerville, 2014) found test results on some materials tested by other researchers that were used as a guide for the laboratory phase of this research project.

Partial Depth Repair

There are a wide range of solutions such as full depth repair, partial depth repair, dowel bar retrofit, etc., which have been used for the repairing of concrete pavements and structures that deliver excellent outcomes for some specific applications. Among these, partial depth repairs are defined as concrete pavement restoration methods that remedy localized distress This includes pop-outs, spalls, and scaling in concrete pavements or bridge decks (Federal Highway Administration (FHWA), 2011). Partial-depth repair refers to removing the deteriorated part of the pavement or bridge deck, up to one-third of the slab thickness, and replacing it with adequate repair material. The repair can be applied in two forms: transversely or longitudinally on the pavement, where deteriorations are detected (Federal Highway Administration (FHWA), 2011). Partial-depth repairs restore structural integrity and improve the quality of the ride. The depth of deterioration can vary from a few millimeters to the full depth of the pavement. Once the concrete pavement or bridge deck start deteriorating, spalls begin to grow and propagate under traffic loading and repeated thermal stresses. Technically, the partial-depth concrete repairs can be used to repair scaling, spalls, and joints where concrete distresses such as "D" cracking and alkali reactivity have been a problem. Partial depth patching can be very effective, when it is adequately placed and lasts for remaining life of the pavement or bridge deck. Size, cost, air temperature, and the amount of time allowed for the repair are factors that affect the selection of the material needed for such a project. Materials like concrete, portland cement, and epoxy resin are those that can be used as the patching materials (Federal Highway Administration (FHWA), 2011).

Studies show that proper installation of partial-depth patches using appropriate quality control practices, can makes 80 to 100% of the repairs perform well for over ten years of service. However, installed patches may exhibit poor performance, which is due to a combination of improper design, construction, and poor quality control and inspection (Wilson, Smith, & Romine, 1999).

Dimensional stability is another parameter that affects the success and durability of the project. It is a function of two primary factors: creep and shrinkage. Creep is known as deformation of concrete when subjected to continued loads. This deformation occurs in concrete at all stress levels within its service stress range, and includes an instantaneous deformation that is then followed by a slow increment. On the other hand, concrete itself exhibits slow deformations in time that is referred to shrinkage. Shrinkage is a volumetric change in concrete, which is due to long-time chemical processes and changes in moisture content. The difference between the moisture content at the top and bottom surfaces of the concrete slab forms a dimensional gradient that develops through the depth of the slab. This produces warping and cracks that result in poor serviceability and performance of concrete slabs. To differentiate between these two types of time-dependent dimensional changes, creep is usually referred to the difference in dimensional change between a loaded and an equally old identical specimen. It is worth noting that the instantaneous elastic deformation, which occurs under applied stress, is distinguished from the creep deformation.

Therefore, in case of dimensional stability, if the stress becomes large enough, cracking or loss of bond at the interface can be observed. On the other hand, even if the material is strong enough to resist cracking, high stresses can still be developed due to the different shrinkage properties between the patching material and substrate, which will result in interfacial cracking. Table 1 summarizes the most common causes of failure in partial-depth patching of concrete pavement and bridge deck.

Table 1. Causes of failure in partial depth repair (Wilson et al., 1999)

Causes of partial depth patch Failure	
Design issues	Construction issues
• Lack of bond between the patch and the original pavement or bridge deck	• Improper selection of repair materials
• Incompatibility between the thermal expansion of the repair material and the original slab	• Incompatibilities in the climatic conditions during repair placement
• Variability of the repair material	• Insufficient consolidation
• Incompatibility between the joint bond breaker and the joint sealant material	• Exclusion of some deteriorated concrete from repair boundaries

Bonding in concrete pavement patched material

When a repair is conducted, stress distribution and bond specifications of the repair system is mostly influenced by the differences in the properties of the substrate and repair material. Different modulus of elasticity and thermal movement of the two materials, causes each layer to show different strains when exposed to a same load, as well as temperature strain.

In addition, as discussed in former section, shrinkage is another factor that increases the interface vulnerability, when a new patch is performed. Therefore, as the most critical part of a repair system, the interface should have enough resistance to deliver these differences between the old and new patched layer. Therefore, achieving an adequate adhesion at the interface is considered a key factor of an appropriate repair process. In that case, a repair system can be considered as a three phase composite system: substrate, patching material/overlay, and the interface and vicinity of bond zone (Bakhsh, 2010). The interface and bond zone must be able to carry the stresses, which are imposed on the system. There are many factors that affect bond specifications that some of them will be discussed in the following sections.

Definition of Bond Strength

The main objective of concrete pavement and bridge deck repair is to restore the load carrying capacity and the stiffness of deteriorated concrete member. Accordingly, monolithic action is the final goal that requires adequate bond between the patched layer and the substrate (Silfwerbrand, Beushausen, & Courard, 2011). The bond strength is defined as adhesion between new repair material and substrate that can be the most uncertain link of the repair system. Sufficient bond strength is the main parameter to have a sound repair system (Beaupré, 1999). The bond or adhesion specifications can be considered from two different points of view (Courard, 1999); the quantitative measure of the magnitude of bond, which often is expressed as the required stress or energy to detach the two materials, and the conditions and kinetics of joining two materials that involves two different bond behaviors. It is crucial to choose one that can better govern the stresses subjected to the pavement and bridge deck in the field.

Main Factors Affecting Bond Properties

Fresh material properties

Fresh material properties play an important role, both for bond durability and bond strength development. Workability and compaction of the freshly placed patching repair material affect the potential to fill open voids on the surface of the substrate concrete (Silfwerbrand, 2003). Normally, premixed mortars are applied for small repair patches. However, more efficient contact area and therefore higher bond strength are expected when self-consolidating repair materials (with high fluidity and enough viscosity) are applied.

Hardened material properties

Generally, in hardened state, the influence of the compressive strength of the repair material on the bond strength of the composite is not significant. However, tensile strength is an important parameter to consider as it is in a direct relationship with crack development and so, affects the generation of boundary conditions that may participate in initiation of debonding. Delatte et al. (Delatte, Williamson, & Fowler, 2000) demonstrated that an increase in early age concrete strength significantly increases both tensile and shear bond strength.

In addition, dimensions of the repair patch are another factor that can influence the durability of the bond. This is due to the effect of dimension elements, such as area and thickness, on forming the stresses at the interface that are due to the differential movement between the patched repair material and substrate (Silfwerbrand, 2003). Generally, small repairs exhibit more resistance to crack than larger areas. However, there is no general agreement on how the repair thickness influences the bond properties. Laurence et al. (Laurence, Bissonnette, Pigeon, & Rossi, 2000) showed that the possibility of bond failure depends on bond strength and bond stress, simultaneously, and thickness is expected to influence the bond stress (Bissonnette, Courard, Fower, & Granju, 2011). Therefore, based on their findings, thickness of the repair affects the possibility of the bond failure not the bond strength. On the other hand, Banthia and Bindiganaville (Banthia & Bindiganavile, 2001) concluded from their measurements that the thickness of a repair directly affects the bond strength between the repair material and the substrate so that the thicker the repair is, the higher the bond strength would be.

The bond between substrate and new repair material is very similar to interface between aggregate and cement paste. Based on a research performed by Pigeon and Saucier (Pigeon & Saucier, 1992), a wall effect exists between patching material and substrate that results in a transition zone and therefore forms a weakened layer. Figure 4 shows this in detail.

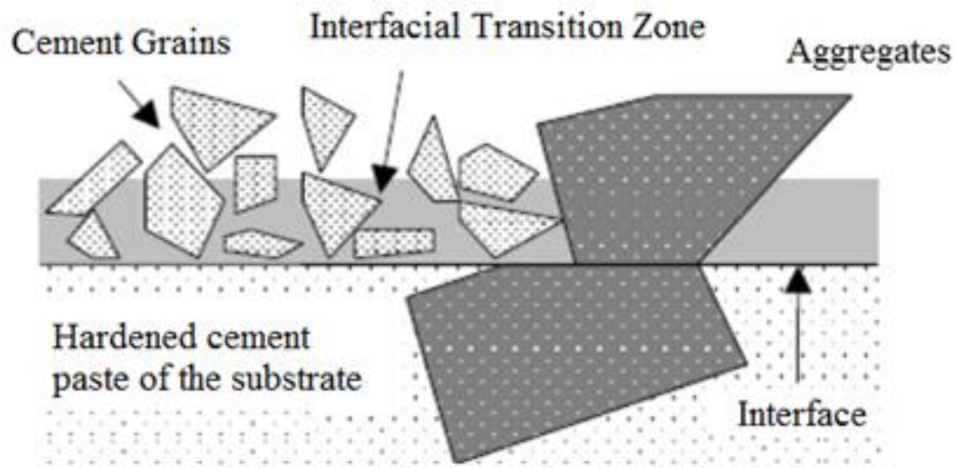


Figure 4. Transition zone between substrate and patching material (Pigeon & Saucier, 1992)

Other factors that influence the bond properties, which need to be considered, are:

- Cleanliness

Any type of contaminant like dust, oil, grease, etc., can significantly influence the bond strength if remain on the surface. They make a deterrent layer for interlock between substrate and new layer and as a result reduce the friction between the layers. Among these, dust can be easily blown off (Austin, Robins, & Pan, 1995; Silfwerbrand, 1990).

- Surface preparation

Surface preparation has an influential effect on bonding in the interface. Therefore, to achieve appropriate bond strength it is important to prepare the surface of the substrate properly prior to performing the patching operation. Depending on the type of repair, there are different techniques available to prepare the surface. It is crucial to select the most appropriate method.

Micro cracks are one important parameter that should take into consideration when preparing the surface. If the surface produced by a vigorous technique such as hammering, the surface will be very rough, However, micro cracks will be induced just beneath the prepared surface (Silfwerbrand, 1990; Talbot, Pigeon, Beaupré, & Morgan, 1995). Micro cracks have a deteriorating influence on the top layer of the substrate and reduce bond strength substantially. They reduce the effective bond area and may develop due to the stress concentration.

According to the field test results, if mechanical removal is followed by high pressure water cleaning, the bond strength can achieve acceptable values (Courard, Bissonnette, & Belair, 2006; Silfwerbrand, 1990).

- Laitance

Laitance refers to a weak and nondurable layer of material that is made of cement and fines, which are brought to the top of the wet concrete by bleeding water (Portland Cement Association (PCA), n.d.). When the substrate is concrete, removing the laitance from the surface of the substrate must be considered. Presence of laitance can reduce the bond strength. Sandblasting is one of the appropriate ways to remove the laitance.

Classes of Repair Materials

Ordinary portland cement concrete (OPCC) is still one of the most commonly used patching materials for repair of concrete pavements and bridge decks. It is most efficient when full-depth patches or complete slab replacement are taken into consideration, while its application for partial-depth repair has shown diversity of results (Unified Facilities Criteria (UCF), 2001). Although, this type of repair material is sufficient for repair, OPCC requires prolonged traffic lane closures. In addition, there has been a need to develop materials capable of extending the service life longer than 20 years in harsh environments with a minimum of maintenance (Muñoz, 2012). When desired, a properly designed and constructed bonded high performance repair material can add considerable life to an existing pavement, by taking advantage of the remaining structural capacity of the original pavement. Consequently, novel products with more sensitive mixture proportions and developed components were developed to reduce the durability concern.

On the other hand, to minimize disruption to the traveling public, it is necessary to have a quick repair of pavements or bridges that also improves safety on roads. In this setting, the term 'quick' describes materials that gain strength at usually one to three hours after casting that will allow the repaired section of road to place back into service within a short period. These materials are known as rapid-hardening materials. According to definition presented by US Army Corps of Engineers (Priddy, 2011) rapid-hardening is referred to those materials that can obtain a minimum compressive strength of 3,000 psi (20MPa) within eight hours or less. These materials, though, due to their constituents, may exhibit poor performance in some specific service environment. Some of these materials are susceptible to sulfate attack and/or alkali aggregate reactivity, since they contain high levels of alkali or aluminate to provide expansion. Therefore, their exposure to reactive aggregates and sulfates should be restricted. Many types of these materials are available in the market consisting of: Type III portland cement, regulated-set portland cement high alumina cement, magnesium phosphate, gypsum-based, polymer concrete, and polymer modified concrete. A general classification of these materials include three groups; cementitious mortars, polymer-modified cementitious mortars, and resinous mortars

(Emberson & Mays, 1990). More specific classifications are offered by ERDC and NTPEP. ERDC groups the rapid-hardening materials into base materials, ultrafine portland cement, magnesium phosphate, and high alumina. NTPEP categorize this type of material into three families of cementitious concrete, polymer concrete and polymer modified concrete.

It is often a problem to identify the specific cementitious agent, since many different products are sold under a variety of trade names. All claims of performance for these proprietary products should be treated with caution, and it is always thoughtful to establish the performance of new products through trials before committing to the purchase of large quantities (Unified Facilities Criteria (UCF), 2001).

ACI 546R-04 lists some of the available materials for repairing concrete structures into two general groups; cementitious materials and polymer materials.

Cementitious Concrete

Rapid setting cementitious materials are generalized by short setting times. Some may reveal rapid strength development with compressive strengths in excess of 2400 psi (17MPa) within three hours. The classification given to the rapid setting repair materials is determined by composition, and is the main factor determining what type of patching material is suitable to use.

Accelerated strength development is one advantage to rapid setting cements that allows the repaired pavement or bridge deck to be open into service more quickly than conventional repair materials. It makes lower traffic-control costs and improves safety. On the other hand, even though most rapid-setting materials are as durable as concrete, some may not perform well in a specific service environment which is known due to their constituents. ASTM C928 (ASTM C928-13, 2013) is the standard used to cover packaged, dry, cementitious mortar or concrete materials for rapid repairs to hardened hydraulic-cement concrete pavements and structures.

Polymer Concrete

Polymer concrete is a constructional composite in which portland cement is completely replaced with polymer binder materials. Comparing to OPCC, specific features of polymer concrete materials like high strength and low weight, very good bonding properties, and low permeability made it a very appropriate material in different construction industries such as bridge decking, pavement overlay, and concrete crack repair (Heidari-Rarani, Aliha, Shokrieh, & Ayatollahi, 2014; Issa & Debs, 2007; Reis & Ferreira, 2003; Ribeiro, Reis, Ferreira, & Marques, 2003; Shokrieh & Heidari-Rarani, 2011).

On the other hand, creep and high sensitivity to temperature are the major problems of polymer concrete. These are related to viscoelastic properties of the polymer. Besides, temperature variations markedly influence the mechanical properties of polymers, especially within the glass transition temperature range (Agavriloaie, Oprea, Barbuta, & Luca, 2012; Ribeiro & Nóvoa, 2004; Tavares & Ribeiro, 2002) . The glass transition may occur between 68°F (20 °C) and 176°F (80 °C) for many polymers used in civil engineering (Yang, Huang, Li, & Chor, 2005).

Magnesium Phosphate Concrete

Magnesium phosphate concrete is a hydraulic cement based system. In contrast with portland cement concrete and polymer cement concrete, which require moist curing for optimum property improvement, these systems produce their best properties with air curing. These materials have been used in concrete repairs since the 1970's. They are generally self-leveling and set quickly. They have low permeability, good bond strength to portland cement, and perform better for thin patches, because they do not require a moist cure.

On the other hand, there are some limitations of magnesium phosphate concretes. they should be extended only with non-calcareous aggregates like silica, granite, basalt, and other hard rocks. This is because the bond can be suffered from a poor paste aggregate bond caused by the presence of carbon dioxide. Carbon dioxide is the result of carbonated surface reaction with the phosphoric acid. Its properties are very sensitive to the water content specified by the manufacturer, and any variation of the water content reduces both the strength and the durability of the Magnesium phosphate concrete.

Polymer Modified Concrete

Polymer modified concrete is a portland cement concrete with polymer solutions (such as latex modifier and magnesium phosphate) added to the mix to achieve certain properties. Similar to portland cement concrete, the primary curing mechanism for polymer-modified concrete is hydration of the cement binder (Ergon's Corrosion Engineering Inc., 2008). Polymer modified concrete may be classified into two classes: latex modified concrete (LMC) also known as polymer portland cement concrete and polymer impregnated concrete (PIC) (Mindess, Young, & Darwin, 2003). LMC is a new generation of conventional concrete, which is made by replacing part of mixing water with a latex. PIC consists of impregnation of precast hardened portland cement concrete with a monomer that is subsequently converted to solid polymer. For this study, PIC is not used, as replacing the damaged concrete is concerned, not repairing the damaged concrete. Both types of polymer modified concrete have higher strength, lower water permeability, higher chemical resistance, and greater freeze-thaw resistance than normal concrete (A. Blaga, 1985). Polymer modified concretes are typically less expensive than polymer concretes and are often used for concrete restoration work when construction time is limited. (Ergon's Corrosion Engineering Inc., 2008).

Typically, the primary weaknesses of the polymer materials are the mismatch of their thermal expansion coefficients with that of substrate concrete, their sensitivity to curing conditions and their poor performance at high temperatures (Muñoz, 2012). These features highlight the potential for alternative solutions. For these purposes, high performance repair materials offer high mechanical properties and a rapid setting behavior. Table 2 is part of the table summarized by ACI committee 546R (ACI Committee 546R-04, 2004). It illustrates some of the most commonly used repair materials.

Table 2. Comparison of the most common repair materials (ACI Committee 546R-04, 2004)

	Material	Advantages	Limitations	Applications
Cementitious Materials	Conventional concrete	Easy to handle. Low cost.	Not appropriate in harsh environment. Potential problems due to shrinkage.	For thick sections and large volumes of materials.
	Conventional mortar	Easy to handle. Low cost.	Greater drying shrinkage. Not adequate in harsh environment.	Same applications as conventional concrete but for small repairs
	Cement grouts	Easy to handle. Low cost. Minimum shrinkage.	Usually the minimum crack width should be about 1/8 in.	To fill large dormant cracks around or under a concrete structure.
	Magnesium phosphate concrete and mortars	Similar handling to NSC. Rapid strength gain. Short setting times.	Potential carbonation problems. Poor strength against impacts.	When short down time is essential (overlays, airports). Cold weather.
	Preplaced-aggregate concrete	Low shrinkage. No segregation. Underwater repairs.	Skilled labor.	Extensive repairs. When placing might be an issue
	Rapid-Setting Cements	Short setting times.	Not appropriate in harsh environment.	When short down time is essential.
	Shrinkage-compensating concrete	Minimum shrinkage cracking, joints to control shrinkage are not necessary	Not appropriate in harsh environment. Skilled labor for mixing, placing and curing.	Minimum shrinkage in slabs, pavements, bridge decks and structures.
Polymer Material	Polymer-impregnated concrete	Improvement of durability characteristics.	Durability issues if not all cracks are sealed.	Wide range of applications. Long-term performance.
	Polymer-modified concrete (Latex Modified Concrete)	Excellent long-term performance. Minimum bond failure. Similar handling to NSC except the curing treatment.	Placing and curing at 45 to 85° F. Susceptible to shrinkage cracking during placement. Modulus of elasticity lower than that of concrete.	Mostly used in overlays for bridge decks, parkings and floors.
	Polymer concrete	Rapid curing. High strength. Similar handling to NSC.	High coefficient of thermal expansion. Modulus of elasticity might be lower than that of concrete.	When short down time is essential. Repairs where only thin sections can be applied. High protection against chemical attack.

Repair Process

The repair process includes many steps, which control the success of a repair. Failure in any of these steps may cause the failure of the whole repair system. Removal of existing damaged concrete, adequate surface preparation of the repair patch, selection of the product, placement conditions, and procedures required by the manufacturer all affect the outcome of the project.

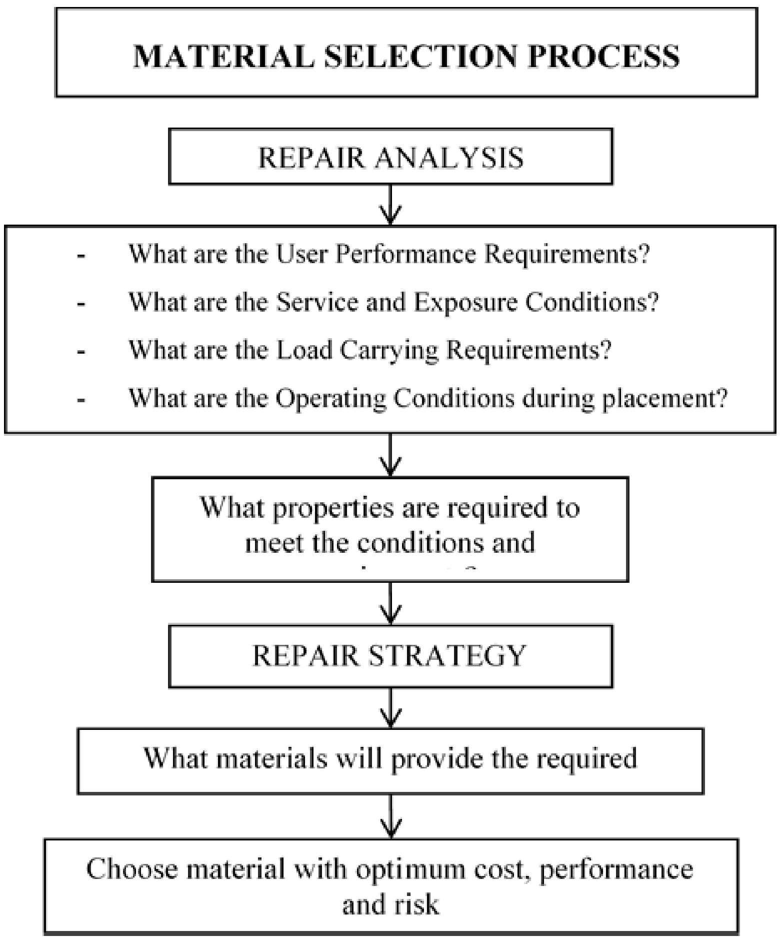


Figure 5. Questions to Consider Before Selecting a Repair Material. based on (R. Emmons, 1993)

Some questions need to be asked when considering the repair approach for a damaged section of pavement or bridge deck. Figure 5 shows an example of these questions. The repair products will be installed in an environment where severe freezing and thawing, chloride exposure, and drying and wetting occur.

The products also are generally placed while traffic continues in neighboring lanes, making it crucial that lane closures are for the least time possible. A two to four hour window is the target to ensure minimal delays and safety for workers.

Survey of Selected Repair Materials

Select of a repair material is not easy and involves an understanding of many parameters. Some of these parameters are highlighted as follows:

1. Structural requirements (Bond strength)

Includes load carrying and stress distribution. This requires a good bond to the existing material and a similar modulus of elasticity or strength to the existing concrete. The bond strength between the new and old materials is vital for the success of a repair project. A satisfactory bond provides strength under different loadings scenarios at least equal to that of the substrate. The interface has to withstand the stresses that are caused by restrained volume changes or loads.

2. Constructability (Fresh properties)

Requires speed and avoidance of special requirements to get the patch installed quickly and easily. The key is to maintain rapid setting qualities but still allow sufficient working time. For this purpose, rapid setting materials are highly advantageous to accelerate the repair process.

3. Exposure conditions (Durability)

Exposure conditions, namely chlorides and freezing and thawing, are important for patches. Thermal coefficient of expansion, permeability and drying shrinkage are other properties to pay attention to when dealing with these conditions. The patching repair materials should provide enough protection against all these factors that can deteriorate the structure. The success of the repair and its final service life is highly depended on the performance of the repair material as a barrier (P. Emmons & Vaysburd, 1996).

4. Cost

The cost for repairs varies remarkably depending on size, number, and location of repair areas, time and traffic volume, cost of the materials used, lane closure, and labor. Among these, cost of repair material has the most significant effect on the final selection of the repair material. However, it should not be put before the required performance characteristics. A poor choice of repair material would cause earlier failure of the repaired region.

Selected Products

From both the literature search and the performance surveys 6 different products were selected by Sommerville for testing (Sommerville, 2014). Moreover, according to the literature review performed by the author, two more materials, Pavement SLQ and PaveSaver, were added for further laboratory investigations. Table 3 summarizes the information on the chosen concrete repair products. Each product manufacturer was contacted to obtain additional product information, as well as to order material for testing.

A list of States was put together that represent similar climates to Ohio, to see if any of the concrete repair materials were already approved in these States. The list included New

York (NYDOT, 2012), Minnesota (MNDOT, 2013), Wisconsin (WIDOT, 2014), Michigan(MDOT, 2012), Colorado (CODOT, 2011) and Pennsylvania (PNDOT, 2014).

Table 3. Types of Repair Materials Selected

Product name	Material Type	State DOT Approval (NY, OH, MN, WI, MI, CO, PA)
Flexset	Polymer	-
MG Krete	Magnesium Phosphate	PA
Delpatch (Delcrete)	Polymer	-
SR- 2000	Polymer	-
FastSet DOT Mix	Cementitious Material	OH, WI, CO, PA
Repcon 928	Polymer Modified	NY, MN, WI, CO
Pavesaver	Polymeric	-
Pavement SLQ	Cementitious Material	NY, MN

A brief outline about the final products, their composition, and a general summary of their properties are presented in Chapter 3. It is worth noting that due to their temperature range and excellent research results, FlexSet and MG-Krete are first two products chosen to be the winter testing materials, since these were the only materials recommended for use in low temperature.

Selected Product Information

After communicating with product manufacturers, information of the products was collected one by one to identify the basic information on each of the products; surface preparation, product usage, special equipment, and materials costs are some of these information. Table 4 summarizes this information for each product selected for testing in this project.

Table 4. Product Information Summary

Product name	Cost/ ft^3 (m^3)	Traffic Acceptance (hour)	Special Equipment	Concrete/Asphalt Repair	Repair Preparation
Flexset	$235.00 ($8299)	1/2	No	Concrete	No cleaning
MG Krete	$122.22 ($4316)	1/2	No	Both	No Cut/ Clean
Delpatch (Delcrete)	$232.43 ($8208)	1	Hobart or Drill Mixer	Concrete	Sandblast, Cut, Blow, Clean, Tape
SR- 2000	$175.00 ($6180)	2	No	Concrete	Total Clean
FastSet DOT Mix (Quikrete)	$11.32 ($399.7)	1 ½	No	Concrete	Cut, Clean, Roughen, Water blast
Repcon 928	$57.36 ($2025.6)	1 (Foot Traffic)	No	Concrete	Clean, Cut, Sandblast
Pavesaver	$230.00 ($8122.4)	3	Jiffy Style Mixer	Concrete	Sandblast, Cut, Clean
Pavement SLQ	$166 ($5862)	1	drill and paddle	Concrete	Cut, Clean, Roughen, Water blast

CHAPTER III

SELECTION

Final Product Recommendation

As stated in the previous chapter, because of their low temperature range during the installation, compliance of most ODOT and ASTM 928 laboratory requirements, and excellent previous field-testing results obtained by ERDC and NTPEP, FlexSet and MG Krete were obvious choices. The additional four products recommended by A. Sommerville (Sommerville, 2014) were Delpatch, RepCon 928, SR-2000, and Quikrete. This includes a total of six; three polymer materials, one polymer modified material, one portland cement, and one Magnesium Phosphate material. Additionally, Pavesaver and Pavemend SLQ were added to the list of the selected products to be evaluated in the laboratory phase of the project.

Flexet "Roklin System Inc."

FlexSet is a self-consolidating product produced by Roklin Systems incorporated. It is a two part, A and B polymer concrete. It was originally developed as a rapid runway concrete repair system for the military, which is now used as an alternative to traditional concrete restoration such as; driveway concrete repair, floor repair and spall repair (Roklin Systems Inc, 2014).

FlexSet is packaged in 5 gallon (20 L) sealed, plastic pails. Each kit contains ½ gallon (2 L) each of specially formulated A and B polymers, 30 pounds (14 kg) of polymer coated sand, and 12 pounds (6 kg) of uniformly graded polymer coated topping sand which will deliver 0.4 ft^3 (0.01 m^3). A 25-pound (11 kg) bag of 3/8 inch (10 mm) polymer coated basalt aggregate can be used to extend the material. This is bought separately (Roklin Systems Inc, 2014).

It is important to make sure there are equal parts of both A and B polymer when mixing the materials together. Depending on the required fluidity, the amount of extender aggregate added is up to the user. Polymer A should be added first and fully mixed with the sand before polymer B is added. If an accelerant is needed for cold weather this should be included to the B polymer before it goes in the main mixture. Utilizing naturally rounded polymer coated sand in FlexSet material greatly enhances flowability and increases the overall strength of the crack repair. The material has a 9 to 12 minutes working time at 75°F (24°C). It has a wide temperature range of -10°F +160°F (-23°C - 60°C), making it one of only a few materials that can be placed at the extreme hot and cold temperatures (Roklin Systems Inc, 2014). Roklin recommends a motorized pail mixer for mixing procedure to ensure a good dispersion of polymer and aggregates.

FlexSet was tested by NTPEP in 2006. According to the report from NTPEP, FlexSet had no mid panel cracks, delamination or spall after 1 year but exhibited 1/16” (1.6 mm) of edge crack width. After two years it still has no mid panel cracking or spalling but has 22% delamination and 1/16” (1.6 mm) to 1/8” (3.2 mm) of edge cracking.

MG Krete “IMCO Technologies Inc.”

MG Krete is a two component, magnesium phosphate based, high early strength repair material produced by IMCO, suitable to cure in all weather and temperatures greater than 14°F (-10°C) (IMCO Technologies Inc., 2014).

It is packaged as a 50-pound (23 kg) bag of dry compound and 1 gallon (3.8 L) of liquid activator. By maintaining the mix ratio supplied of one container of liquid to one bag of compound, it will give a trowellable consistency. However, the ratio may be adjusted to suit the needed application by increasing either of the two components. Up to two scoops of accelerant can be used per kit. It is not needed when the temperatures exceed 40°F (5°C).

Concrete repair is its ideal use, but it can also be used in asphalt repair if the surface is rigid. When mixing, to ensure a good blend, it is desired to use only half of the sand and liquid at once. Pea gravel may be used to extend the product, but needs to be clean and dry; otherwise, the product will most likely fail due to poor bond. Water will ruin the integrity of the mix, so the patch location must be completely dry. Using more aggregate slows down the setting process by absorbing more heat. Moreover, due to the hydration reaction, the deeper the patch, the hotter the repair will become during the setting time. A green ammonia smelling slime and gas will be produced on the surface from this reaction (IMCO Technologies Inc., 2014). MG-Krete is a rigid material with a set time of 15 minutes at 68°F (20°C). The compressive strength, flexural strength, length change, freeze thaw resistance and scaling resistance all satisfy ODOT and ASTM 928 requirements. Under the state approval list, using states similar to Ohio, Pennsylvania was the only one to have approved this product for rapid pavement repair, but it is approved in province of Alberta, Canada.

Delpatch (Formally Delcrete) "D.S Brown"

Delpatch, also known as Delcrete, is a two-part polyurethane elastomeric concrete that can accept traffic within one hour after final pour. Delcrete has wide applications in concrete pavements due to its flexibility, anti-spalling property, and high load bearing capacity. The typical Delcrete application is in concrete spall repair patching or bridge expansion joint work (D.S. Brown, 2015b). It is not to be used in asphalt repair. Delpatch comes as a bag of sand and fiberglass, part A and B polyurethane liquid and primer. The primer can be sprayed or brushed into the hole. Mixing of the material asks for 100 ounces (3000ml) of Part A and 50 ounces (1500ml) of Part B measured out using beakers. These liquids are added to the mixing bowl and the mixer is started at a slow speed. Immediately the sand/fiberglass mixture is added at a gradual rate. The mixer is then increased to a medium speed until an even grey color indicates an even mix. It is specified that a Hobart, drill or pail mixer be used when mixing the material. A 1 inch (25 mm) minimum application depth is required and it must be installed at 45°F (7°C) or higher. There cannot be even slight rain when it is poured and on hot, sunny days, the kit must be kept under cover or in the shade (D.S. Brown, 2015b).

Since it is a polymer concrete, it is a flexible material with a modulus of elasticity of 7.44 psi (510 MPa) and has an elongation at break of 25%. Delpatch was not in any of the

NTPEP or ERDC studies, and had not been approved in any of the state DOT's chosen to represent similar climates to Ohio.

SR-2000 "Southeast Resins Inc."

SR-2000 produced by "Southeast Resin Inc." is a polymer concrete composed of a two part polyester resin used to restore damaged concrete and asphalt. It is a flexible product, using the same compound for both applications (Southeast Resins Inc, n.d.).

To lay the repair patch the hole needs to be clean of loose materials, have no dust or oil and must be primed with the resin part of SR-2000. The kit comes as liquid resin and a bag of #30 grit aggregate, which is clean and dry. Pea gravel can be added to extend the product. A non-slip top coat can be added if required. It can return to traffic within 2 hours after the repair is complete and requires no expensive equipment (Southeast Resins Inc, n.d.). SR-2000 can be used in temperatures ranging from 35°F to 120°F (2°C to 50°C). (Southeast Resins Inc., 2012).

Quikrete – FastSet DOT Mix

Quikrete is a portland cement, fiber reinforced, rapid setting repair material. It can be used at a thickness of ½" (13 mm) to 2" (51 mm) and can be extended by up to 25lb (11 kg) to repair roads and bridges, which have a minimum thickness of 2 inches (51 mm) (Quikrete, 2012).

No primer is required for bonding. The Quikrete comes in 55lb (25 kg) bags. The bag is added to 1 gallon (3.8 L) of water and mixed for three minutes. The water can be adjusted as necessary to achieve the required consistency but without exceeding the recommended slump range of 3" - 7" (76-178 mm). The 55lb (25 kg) bag can be extended with 25lb (11 kg) of high quality ASTM C33 size number 8 aggregate (Quikrete, 2012).

Its compressive strength, flexural strength psi, length change, and bond slant shear values pass both the ODOT and ASTM C928 requirements. (Quikrete, 2012).

FastSet DOT Mix has been approved by Wisconsin, Colorado and Pennsylvania on the list of states chosen to represent similar climates to Ohio. It has also been approved in Ohio already. This testing serves as a baseline for the other materials.

RepCon 928 - SpecChem

RepCon 928 is a fiber reinforced, polymer modified, single component, rapid setting concrete repair mortar. Because of its corrosion inhibitor properties, RepCon is frequently used on applications that require early resumption of traffic or use, such as concrete floors, highway pavements, bridge decks, etc. It is formulated to meet the requirements of ASTM C928 and AASHTO T260 (SpecChem, 2010).

Surface preparation for the patch needs to be in a saturated-surface-dry (SSD) condition with no standing water on the surface, in addition of being clean and free of loose materials. No primer is needed. Edges should be saw cut and 1/8 inch (3.2 mm) deeper than the depth of the repair. Mixing procedure includes 4.75 to 5.0 pints (2.2 to 2.4 L) of water per 50lb (23 kg) bag and a mortar mixer or drill. RepCon can be extended with clean, SSD, 3/8 inch (9.5 mm) aggregate up to 60% by weight. The optimum temperature range for installing the patch is 65°F to 85°F (18 to 29°C) but can be installed in temperatures as low as 45°F (7°C) (SpecChem, 2010). Additionally, obtained results by NTPEP confirmed that RepCon 928 (NTPEP, 2007) is very freeze thaw resistant. RepCon 928 has been approved by New

York, Minnesota, Wisconsin and Colorado on the list of states chosen to represent similar climates to Ohio.

Pavesaver – D.S. Brown

Pavesaver is a non-shrink epoxy-based, 2-part polymeric, elastomeric concrete used to fix spalls and cracks on airfield, bridge decks, bridge expansion joint headers, and highway pavements. It has great flexibility and strength to provide excellent long-term patching solutions (DS Brown, 2005). Pavesaver is packaged as Part A (grey liquid), Part B (clear liquid) and a 50 pounds (23 kg) bag of aggregate. It does not require a primer, which cuts down on the time it, takes to install the patch. There is a critical mix formula; 2000 ml (68 ounces) of Part A and 2300ml (78 ounces) of Part B and 53.5lb (24 kg) (2 bags) of sand and aggregate. Parts A and B should be mixed first for 30-60 seconds. Before placing this mixture, the repair area needs to be cut, free of loose material, sandblasted and dry. The temperature should be greater than 40°F (4°C) when placing the material. It bonds well to concrete and has a one day compressive strength greater than 3500psi (24 MPa) using ASTM 579-B (DS Brown, 2005).

Pavemend SLQ

Pavemend SLQ is a single component powder cementitious material introduced by Ceratech, Inc. It is water activated, very rapid setting, and self-leveling structural repair mortar and suited for aggregate extension used to repair of bridge decks, pavement, airfields, parking garages, cold storage, anchoring, warehouses, and dowel bar. It is suitable for very rapid concrete repair in a large variety of climates ranging from -20°F (-29 ºC) to

110°F (43°C), especially in near freezing and below freezing applications (Ceratech, 2014). Pavemend SLQ application does not require special mixing or curing equipment.

The Pavemend SLQ comes in 46 lb (20.9 kg) 5 gallon (18.9 L) bucket. The buckets is added to 1 gallon (3.8 L) of water and mixed for a minimum of two minutes. “After adding the water, it is very important to rapidly incorporate all of the dry Pavemend SLQ powders into water to achieve a uniform wet mixture within the first 30 seconds of mixing” (Ceratech, 2014). It has 2-4 minutes working time, depending on the temperature. Pavemened SLQ exhibits a minimum compressive strength of 3000 psi (20 Mpa) within 1 hour of final set (Ceratech, 2014).

General Properties of the discussed materials are summarized in Table 5.

Table 5. General properties of the recommended repair materials

Product name	General Properties	Set Time (C191)	Compressive Strength (C109)	Coefficient of thermal expansion (CRD C39)	Flexural Strength (C78)	Length Change (28 days)	Modulus of elasticity (C469)	Bond Strength (C190)
Delpatch (Delcrete)	Flexible	-	-	-		-	7.4 E4 psi	
Flexset	Flexible	-	1 day: 1710 Psi 7 days: 1820 Psi	-	1 day: 740 psi 28 days: 1008 psi	-	1 day: 1.23E4 psi 28 days: 2.36E4 psi	1 day: 203 psi 28 days: 355 psi
MG-Krete	Rigid	15@68°F	45 min: 2610 psi 1 day: 5148 psi 7 days: 5815 psi	-	(C293) 1 day: 670 psi 7 days: 845 psi 28 days: 1405 psi	Dry -0.027%	3.75E6 psi	3 hr: 223 psi 28 days: 3046 psi
SR- 2000	Flexible	-	(C39) >6800 @ 10 days	-	(D 790) 1500 psi	-	-	Exceed Type II (C1059)
Repcon 928	Flexible	40-45 @70°F	3 hr: 3000 psi 1 day: 6145 7 days: 8750	6.30E-6 in/in °F	(C348) 7 days: 650 psi 28 days: 1150 psi	-	4.7E6 psi	-
Quickrete	Rigid	20-45 @73°F	3 hr: 4500 psi 1 day: 6500psi 7 days: 8000 psi	-	2hr: 440 psi	Dry: -0.052% Wet: + 0.024%	2hr: 2.70E6 psi	-
Pavesaver	Flexible		1 day: >3500 Psi	-	-	-	-	>350
Pavemened SLQ	Rigid		1 hr: >3000 psi 3 hr: >4000 psi 1 day: >4500psi 7 days: >5000 psi	28 days: 2.95 in/in °F	(C78) 7 days: >500 psi 28 days: >600 psi	Soak: < 0.020 Dry: < 0.030		1 day: >1200 psi 7 days: >1375 psi

NOTE: 1 psi = 0.00689 MPa

Class S Option 2 Concrete

To investigate the effect of freezing and thawing cycles on a patched pavement, freeze-thaw (F-T) specimens were made in a two layer composite system. The composite specimens were made with half substrate material, class “S” option 2 concrete, and half repair material to test the bond properties of the repair materials under freeze-thaw cycles. Table 6 shows the mixture proportion of Class “S” option 2 concrete, which is defined by ODOT. The aggregate weights are calculated using the following Saturated Surface Dry (SSD) specific gravities; natural sand and gravel 2.62, limestone sand 2.68, limestone 2.65, and slag 2.30. Gravel was used in this study as the aggregate component.

Table 6. Mixture Proportion for Class S Option 2 Concrete per cubic yard (ODOT, 2005)

Quantitates Per Cubic Yard (cubic meter)					
Aggregate Type	Fine aggregate lb (kg)	Coarse aggregate lb (kg)	Cement Content lb (kg)	Water-cement ratio Maximum	Design Yield Cubic feet (m^3)
Gravel	1120 (664)	1710 (1015)	665 (395)	0.44	27.00 (1.00)
Limestone	1290 (765)	1560 (926)	665 (395)	0.44	27.02 (1.00)
Slag	1270 (753)	1370 (813)	665 (395)	0.44	27.01 (1.00)
8% +/- 2% entrained air content					

Note: 1 ft^3 = 0.028 m^3, 1 lb = 0.45 kg

In addition, the assumed specific gravities of Portland cement is 3.15. This concrete proportioning is based on developing a concrete compressive strength at 28 days of 4500 pounds per square inch (31.0 MPa) for Class S with an expected slump value of 2 to 4 inches (5 to 10.1 cm).

General Safety Considerations

It is necessary to consider the hazard cautions prior to using the materials. This sub-section summarizes the common general hazard identifications of the construction repair materials. These identifications include handling and storage, stability and reactivity, health effect, and first aid measures. Besides, beyond the general safety considerations, specific hazard identification of each material is summarized in Table 7.

Handling and Storage

There are some considerations, when handling and storing a repair material. It is important to keep the materials in cool, dry, ventilated storage area, in closed containers and out of direct sunlight. Containers should be stored above the ground and surrounded by dikes to contain spills or leaks. Keep the materials sealed when not in use. If applicable, inhaling dust, contact with eyes, skin and clothing must be avoided. The materials should be handled carefully to avoid creating dust.

- **Stability**

Stability of the stored materials is an important issue to consider. Mostly, the materials are stable under normal condition, in a dry, cold, and non-humid environment.

- **Conditions and Materials to Avoid**

In general, high temperature, sparks, open flame, and moisture are conditions to avoid. However, susceptibility of the materials to a certain conditions should be thoroughly studied prior to using the materials. There may also be materials, which are necessary to be avoided from contact (skin, eye, etc.). These material should be taken into consideration when ordering a repair material, in the time of storage, and during the application of the repair materials. This should be reviewed individually for each repair material. Additionally, polymerization is another hazard identification, which in few cases may occur. In chemical compounds, polymerization take place through a variety of reaction mechanisms that vary in complexity. In polymer chemistry, polymerization is a process of reacting monomer molecules together in a chemical reaction to form polymer chains or three-dimensional networks. Although it can be used to make some useful materials, uncontrolled polymerization can be really dangerous. Considerable heat and high pressure that can burst or explode a container are some of the polymerization hazards. Most MSDSs indicate whether hazardous polymerization reactions can occur for the corresponding material.

- **Health Effects**

Direct and prolonged contact with the materials can cause severe injuries. Eye, skin, ingestion, and inhalation are the main organs that may be affected. Each material may cause different irritation, which have different first aid measure. Therefore, health effect of each material should be studied individually.

  - **Eyes**

Generally, direct contact of the materials with eyes may cause severe irritation, mechanical irritation, and abrasion, redness, burning, stinging or itching. The contacted eyes should be flushed with water for at least 15 minutes while holding eye lids apart and medical attention should be considered immediately.

- **Skin**

Direct, repeated and/or prolonged contact of the materials with skin may cause dermatitis (skin redness, scaling, cracking, irritation and chemical burns). Also, it can cause inflammatory effects to the skin or tissue at the site of contact. In addition, repeated minimal contact may cause sensitization. Materials in contact should be removed from the exposed areas immediately and the residue should be washed off with soap and water. Remove contaminated clothing. Launder contaminated clothing before reuse. If irritation, rash or other disorders develop, get medical attention immediately.

- **Ingestion**

The materials may be toxic or non-toxic. Depending on the type of the material, different cautions should be taken. In case of ingestion, materials may cause irritation to the mouth, throat and stomach. Also, gastrointestinal irritation, stomach tissue, digestive tract nausea, central nervous system damage, and vomiting can be consequences of ingestion. In all cases, vomiting should not be induced. If vomiting occurs, drinking fluids again is necessary. Aspiration of material into the lungs due to vomiting can cause chemical pneumonitis, which can be fatal. Plenty of water should be drunk and the person should be referred to medical personnel immediately. Never anything should be given by mouth to a person who is losing consciousness or is unconscious.

- **Inhalation**

Asthma-like symptoms may occur. These symptoms may include coughing, wheezing, and shortness of breath. A hypersensitive pneumonitis may also occur if the person is sensitized. Overexposure may induce headaches, dizziness, drowsiness or unconsciousness. Chronic exposures may result in permanent decreases in lung function.

If breathed in, the victim must leave the exposure area to fresh air immediately. If coughing and other symptoms persist, the individual should get medical attention. Keep the victim warm, quiet. If breathing is difficult, oxygen should be administered. If breathing has stopped, artificial respiration (mouth-to-mouth resuscitation) should be supplied.

Table 7. Individual Safety Considerations

Materials	Specific Safety Considerations
FlexSet (Part A) (Roklin Systems Inc, 2015a)	**Conditions to avoid** **“**Contact with incompatible materials in a closed system will cause liberation of carbon dioxide and buildup of pressure”. **Materials to avoid** **“**Any material containing active hydrogens, such as water, alcohol, ammonia, amines, alkalis and acids, Some reactions can be violent. Keep away from strong oxidizers such as hydrogen peroxide, bromine and chronic acid.” **Polymerization** **“**May occur at high temperatures, above 204°C (400°F). Possible evolution of carbon dioxide gas at extremely high temperatures may rupture closed containers.” **Decomposition products** **“**Combustion products: carbon dioxide, carbon monoxide, nitrogen oxides, sulfur oxides, ammonia, trace amounts of hydrogen cyanide and unidentified organic compounds.”

Flexset (Part B) (Roklin Systems Inc, 2015b)	**Materials to avoid** **"**Isocyanates and strong oxidizers." **Polymerization** **"**Will not occur." **Decomposition products** **"**Organic vapors and other thermal decomposition products." **Health effects** **"**This material is classified as "Relatively Nontoxic" by ingestion. Injury may be severe and possible fatal in extreme cases."
Delpatch (Part A) (D.S. Brown, 2015a)	**Conditions and materials to avoid** **"**Water, alcohols, amines, strong bases, metal compounds and surfactants may react with evolution of heat and carbon dioxide." **Decomposition products** **"**Hydrogen cyanide, carbon monoxide, carbon dioxide, oxides of nitrogen and isocyanate vapors." **Health effects** **"**May cause severe eye injury, which may not be reversible." **Inhalation** **"**Sensitized individuals can experience asthmatic attacks. High exposures to TDI may lead to bronchitis, bronchial spasm and pulmonary edema (fluid in lungs). Effects can be immediate or delayed."
Delpatch (Part B) (D.S. Brown, 2015b)	**Conditions and materials to avoid** **"**Strong acids and bases, oxidizers and reducing agents, reactive metals such as aluminum or magnesium and other reactive chemicals such as liquid ammonia." **Decomposition products** **"**Chlorine, ortho-chloroaniline, hydrochloric acid, carbon dioxide, carbon monoxide, nitrogen oxides, nitroso amines." **Health effects** **"**Hazardous components are absorbed through the skin. It may cause cancer based on tests in laboratory animals. May produce cyanosis. At room temperature, vapors are minimal due to low vapor pressure. If heated, excessive concentrations are attainable, that could be hazardous on single exposure."

SR2000 (Southeast Resin, 2015)	**Conditions to avoid “**Exposure to excessive heat or open flame, storage in open containers, prolonged storage (6 months), storage above 100 Deg F (38 Deg C), and contamination with oxidizing agents.” **Materials to avoid “**Strong alkalies, strong mineral acids, and oxidizing agents.” **Polymerization “**Possible.” **Decomposition products “**Carbon monoxide, carbon dioxide, low molecular weight hydrocarbons, and organic acids.” **Health effects “**Aspiration of material into the lungs can cause chemical pneumonitis. Excessive inhalation of vapors can cause nasal irritation, dizziness, weakness, fatigue, nausea, headache, possible unconsciousness, and even asphyxiation.”
Pavesaver (Part A) (D.S. Brown, 2015e)	**Conditions to avoid “**No decomposition if used according to specifications.” **Materials to avoid “**Reacts with acids, alkalis and oxidizing Agents.” **Decomposition products “**Carbon monoxide and carbon dioxide, Nitrogen oxides.”
Pavesaver (Part B) (D.S. Brown, 2015c)	**Materials to avoid “**Strong oxidizers and acids.” **Polymerization “**Will not occur. Considerable exothermic reaction with epoxy resins is possible.” **Decomposition** “Carbon monoxide, carbon dioxide, aldehydes, nitrogen oxides.” **Overexposure Effects “**Overexposure to this material can cause chemical burns to the skin and the eyes, and may result in blindness. Can cause allergic skin and respiratory reactions. Vapors may be severely irritating to the respiratory tract. This material is considered a dermal toxicant and may have effects on the central nervous system, liver and kidneys.”
Pavesaver (Part C) (D.S. Brown, 2015d)	**Conditions to avoid “**No decomposition if used according to specifications.” **Materials to avoid “**No dangerous reactions known.” **Decomposition products “**No dangerous decomposition products known.”

MG-Krete (IMCO Technologies Inc., 2015)	**Conditions to avoid** “Oxidizing agents: fluorine, chlorine trifluoride, manganese trioxide, oxygen difluoride.” **Materials to avoid “**Strong oxidizing agents.” **Polymerization “**None.” **Decomposition products “**Silica will dissolve in hydrofluoric acid and produce a corrosive gas (silicon tetra fluoride).”
Repcon 928 (SpecChem, 2015)	**Conditions to avoid “**Not applicable.” **Materials to avoid “**Not applicable.” **Polymerization “**Will not occur under normal conditions.”
Quikrete (Quikrete, 2015)	**Conditions to avoid** “Keep dry until used to preserve product utility.” **Materials to avoid “**Material when mixed with water will react with Aluminum and other alkali and alkaline earth elements liberating hydrogen.” **Polymerization “**None.” **Decomposition products “**Will Not Occur.”
Pavemend SLQ (Pavemend SLQ, 2015)	**Conditions to avoid** “None.” **Materials to avoid** “Acids, ammonium salts, aluminum metal.” **Polymerization** “None.” **Decomposition products** “None.” **Health effects** “May cause upper respiratory tract irritation. High exposures may cause a build-up of fluid in the lungs with severe shortness of breath. Inhalation of silica (dust from sand) can also cause a chronic irreversible lung disorder, silicosis. Some medical reports state inhalation of silica dust may cause lung cancer. Inhalation of calcium carbonate may cause toxic or renal effects.”

CHAPTER IV

EXPERIMENTAL PROGRAM

A comprehensive literature review, searched for other studies that reported on testing the repair materials using standard ASTM testing procedures. Results of these studies (ERDC, NTPEP, ATSSA, etc.) were used to choose the most beneficial tests to capture the primary properties of the repair.

The objective of the laboratory experimental program was to provide some basis to compare the performance of the selected materials in both the laboratory and the field. In addition, the obtained results of these tests can be used in selection of repair materials for future projects.

Laboratory Mixing

Mixing instructions for each product were provided from the manufacturers. All specified procedures were adhered to closely. The high performance rapid setting repair materials were mixed using motorized pail mixer in a five-gallon bucket (18.9 liter) (Figure 6).

Figure 6. Motorized pail mixer

Specimen Preparation

Three 4×8 inch (10×20 cm) inch cylinders of each repair materials were prepared to evaluate compressive strength in accordance to ASTM C39 (ASTM C39-15, 2015). To evaluate the shrinkage of the specimens, two 3×3×12 inch ($7\times 7 \times 30$ cm) prisms were casted according to ASTM C 490 (ASTM C490 - 04, 2004) with two embedded heads at each long end. The specimens were stored in a room with constant temperature of 73 ± 2^{o}F (23 ± 2^{o}C) and relative humidity of 35%. Length measuring of specimens was carried out at day 1, 2, 3, 5, 7 and then once a week up to day 30 and then once a month up to day 105.

Besides, 18 specimens were prepared to evaluate the freeze-thaw resistance of the repair materials. The freeze-thaw specimens were made with half substrate material, class "S" option 2 concrete, and half repair material. 4 ×16 ×3 inch (10 × 40 × 7 cm) freeze-thaw

(F-T) molds were used to cast the materials. All substrate samples were grooved in fresh state to provide proper bonding specification. After casting, all concrete substrates were kept in ambient temperature for 24 hours. Afterwards, the samples were demoulded and cured in water for a minimum of 28 days. Figure 7 shows the concrete substrate preparation.

Figure 7. Preparation of substrate specimens

When the concrete substrates reached at least 28 days of age, they were placed back in the molds and the molds were filled with the repair materials. Figure 8 shows two layer specimens made of substrate and repair materials. After keeping the composite materials in ambient temperature for 48 hr all, the specimens were transferred to the freezer and subjected to the freezing and thawing for up to 300 cycles (10 weeks).

Figure 8. Two layer specimens made of substrate and repair materials

Methods and Testing Procedure

For convenience, the tests and their corresponding ASTM designations are located in Table 8 for quick review.

Table 8. Properties evaluated and test methods

Test	Corresponding ASTM
Freeze-thaw durability	ASTM C666 : Resistance of Concrete to Rapid Freezing and Thawing
Resonant Frequency	ASTM C215: Fundamental Transverse, Longitudinal, and Torsional Resonant Frequencies of Concrete Specimens
Ultrasonic Pulse Velocity	ASTM C597 – 09: Pulse Velocity Through Concrete
Pull-off	Modified version of ASTM C1583 – Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method)
Shrinkage	ASTM C490: Use of Apparatus for the Determination of Length Change of Hardened Cement Paste, Mortar, and Concrete
Compressive Strength	Time interval testing (3 hours, 1day, and 7 days) using ASTM C 39: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimen

Freeze-Thaw

As mentioned before, various natural factors such as low temperature, high temperature differences, drying and watering cycle, freeze–thaw cycles, and wind erosion affect the durability of the concrete pavement in cold climate areas. Among the aforementioned factors, freezing and thawing is one of the major reasons affecting the durability of concrete in such environments leading to its deterioration or failure, due to the pore structure of concrete, (Jin & Li, 2001; Li, Cao, & Xu, 1999; Moukwa, Aitcin, Pigeon, & Hornain, 1989; Ng, Sun, Dai, & Yu, 2014)**.** The deterioration processes during freeze-thaw cycles are repeated, and the material gradually loses its stiffness and strength. Repetitive freezing and thawing can cause deterioration of the concrete by disrupting the interfacial transition zone between paste and aggregate. Freezing of the water leads to hydraulic pressure in capillary pores. If the pressure exceed the tensile strength of the paste or aggregate, it results in the dilatation and rupture of the cavity (Kosmatka & Wilson, 2011). In addition, increasing irreversible expansion is induced. Freeze–thaw seriously affect the durability of concrete (Maslehuddin & Alidi, 2005). Moreover, Some researchers (Sun, Zhang, Yan, & Mu, 1999) previously reported that the deterioration of concrete could be accelerated when subjected to dual-damaging processes, e.g., simultaneously subjected to both external loading and freeze-thaw cycles.

Therefore, freeze-thaw tests were conducted in this repair project and durability properties of the repair materials subjected to rapid freeze-thaw cycles were evaluated. Procedure A of ASTM C666 (ASTM C666-03, 2008), rapid freezing and thawing in water, was followed in lab to conduct the Freeze-Thaw testing procedure. This procedure is used to indicate the variation in both properties and conditioning of concrete and does not offer a quantitative service life prediction.

The freeze–thaw tests were performed on composite beam samples made of repair materials bonded to ordinary cement concrete as the substrate material. The freeze-thaw testing machine used was model H–3185 of Gilson Company, Inc. This machine includes 18 stainless steel containers for concrete specimens. The containers are placed side by side with a heating element inserted between them. To keep the specimens from direct contact they were kept off the bottom of the container by using 1/8- inch (3 mm) brass rods. The cycle started by alternately lowering the temperature of the freezing plate to zero degrees Fahrenheit (-18 ^{o}C) and then increasing the temperature to 40 degrees Fahrenheit (4.5 ^{o}C). The cycle length was kept at 4 hours in accordance with ASTM C666 (ASTM C666-03, 2008).

During the test, at intervals not exceeding 36 cycles of exposure, beam specimens were removed from the freeze-thaw machine. At the end of each interval the machine was stopped while it was in the thawing cycle. To ensure that the specimens were completely thawed and maintained at the specified temperature, they were kept in the machine for a day. The beam specimens were then taken out and washed with water to make them free of scale. Durability measurements were performed after wiping the surface of the specimen free of excess water at SSD condition. The containers were also washed with water to be free of the scale. The specimens were returned to the containers and the test was resumed. This whole procedure was continued for 300 cycles after which the test was stopped and final measurements were taken.

Resonant Frequency

The frequency was taken according to ASTM C 215-02 "Fundamental Transverse, Longitudinal, and Torsional Frequencies of Concrete Specimens" (ASTM C215-08, 2008) with the exception that the hammer impact was slightly different due to the fact that the specimens were composed of two materials. Impact resonant test is shown in details for longitudinal and torsional mode in Figure 9. A precision weighted ball-peen impact hammer, an accelerometer to measure the dynamic response of the specimen and a 1 in (2.5 cm) thick rubber pad to dampen any potential external frequency interference were used. To measure different modes of frequency, the location of impact and accelerator varies. Figure 10 shows the required locations for different modes.

The Relative Dynamic Modulus (Pc) of the composite sample was estimated as using Equation 1. In this research, the Pc was defined as the ratio between the fundamental transverse frequency of a sample after C cycles (n_1) to the fundamental frequency of the sample after 0 cycles of freezing and thawing (n).

$$\boldsymbol{P_c = \frac{n_1^2}{n^2} \times 100} \quad (1)$$

In addition, according to ASTM C 666 (ASTM C666-03, 2008) the following equation applied to calculate the durability factor (DF) of the concrete samples:

$$\text{DF} = \frac{\boldsymbol{PN}}{\boldsymbol{300}} \quad (2)$$

Where, P is the percent of dynamic modulus of elasticity at N cycles, and N is number at which P reaches the specified minimum value for discontinuing the test.

NOTE: "The maximum rapid freeze– thaw cycling times are the maximum cycling times, which simultaneously meet the requirements that relative dynamic elastic modulus is no less than 60%. If P exceed this requirement after ending the 300F–T cycles, then N can be set to 300" [ASTM 666].

(a)

(b)

Figure 9. Impact resonance test (a) Torsional Mode, (b) Longitudinal Mode

The Resonant frequency test carried out to evaluate the Dynamic Modulus of Elasticity and Poisson's Ratio of the repair materials. This test was first developed by Powers from the United States in 1938 (Hassan & Jones, 2012). It is well known as an alternative to the UPV test method. This test is developed to determine the modulus of elasticity of concrete.

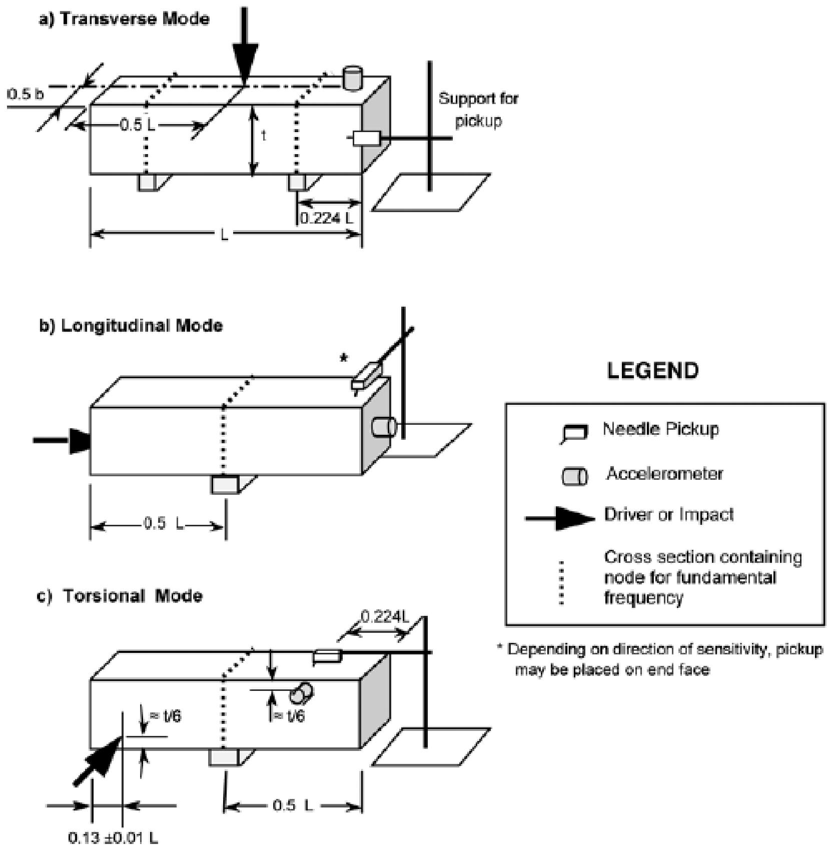


Figure 10. Locations of impact and accelerometer (ASTM C215-08, 2008)

Unlike the UPV method, the resonant frequency test is used only in laboratory evaluations rather than in-situ structural members. Based on the standard, the dynamic modulus of elasticity (E) in Pascal of concrete from the Fundamental Transverse Frequency is calculating using the following equation:

$$\boldsymbol{E = CMn^2} \tag{3}$$

Where, *n* is the fundamental transverse frequency (Hz), M is the mass of the specimen and *C* is 0.9464 ($\frac{L^3T}{bt^3}$) (b and t are the dimensions of the cross section, L is the length, and T is the correction factor of 1.21)

According to the standard, it is important to allow the specimen to vibrate at each end. Once a pulse was sent into the specimen, its response at the peak point was recorded. The experiment was carried out three times for each sample and an average value was calculated in kHz.

Ultrasonic Pulse Velocity

The Ultrasonic Pulse Velocity (UPV) test method was applied to nondestructively evaluate the velocity of a compression wave through the composite specimens. The UPV test conducted is described in ASTM C597 (ASTM C597-09, 2009) and BS 1881 (BS 1881-203, 1989), and is conducted to determine the velocity of sound in a solid material. UPV measures the velocity of a compression wave, which is given by:

$$V = \sqrt{\frac{E(1-\mu)}{\rho(1+\mu)(1-2\mu)}} \tag{4}$$

Where V = compression wave velocity, E = modulus of elasticity, ρ = density, and μ = Poisson's ratio (ASTM C597-09, 2009).

The velocity is mostly a function of the modulus of elasticity. The changes in the wave speed indicate the variability of the modulus of elasticity and the density of the material (ACI Committee 228.2R-98, 1998). This method determines the required time for a vibration pulse in an ultrasonic frequency to transfer through the concrete specimen with known dimensions. Based on the measured velocity, the uniformity, quality, and strength of tested specimens can be estimated. The UPV test can be conducted by three different methods; direct, semi-direct, and indirect method. These methods are comprehensively discussed by ACI 228.2R-98 (ACI Committee 228.2R-98, 1998). The indirect method is the only applicable method for in-situ applications and was used for this research. Figure 11 shows the indirect UPV testing setup.

Figure 11. Indirect UPV evaluation

Mass Change and Scaling Damage

The mass and the length of the specimens were measured at every week not exceeding 36 freeze-thaw cycles and their mass loss and length change were calculated at each set of cycle. In addition, scaling damage was visually evaluated based on the criteria demonstrated in Table 9 (Wang, Nelsen, & Nixon, 2006).

Table 9. Visual rating of scaling damage (Wang et al., 2006)

Rating	Description
0	No Scaling
1	Slight Scaling (small flakes, <1cm^2, Visible on sample surface)
2	Slight to moderate scaling (large flake visible on sample surface and sample edge damage noticeable)
3	Moderate scaling (sample edge damage and some coarse aggregate visible)
4	Moderate to severe Scaling
5	Severe scaling (chunk coming out of surface and edges, scaling depth >0.3cm, and coarse aggregate visible over entire surface)

Pull off Test

The pull-off test is a tensile test, which evaluates the bond strength. It is a relatively simple test, which can be carried out for both field and laboratory investigations evaluate the material properties and failure modes (Austin et al., 1995; Chmielewska, Czarnecki, & Krupa, 2003; Vaysburd & McDonald, 1999). It is common to measure the adhesion strength of an adhesive material that bonds a repair material to a deteriorated concrete pavement or bridge deck. However, different factors like coring depth into substrate, strength of the substrate concrete, and etc., affect the results of pull-off test (Chmielewska et al., 2003).

Basically, the pull-off test includes a direct tensile load (F_T) on a partial core that mobilizes the repair material, the bond line, and a portion of the substrate until failure occurs (Bonaldo, Barros, & Lourenço, 2005). A loading device, applies the load to the pull pin at a constant rate. Once the test is conducted, the failure mode has to be carefully analyzed, because it provides information about what was really measured (Chmielewska et al., 2003). Figure 123 demonstrates the principle of the pull-off test, and sketches a typical failure surface for the case of repair and adhesion strength higher than the pull-off strength of the concrete substrate (Bonaldo et al., 2005) . Following completion of the test, different failure characteristics may be observed at the bond surfaces. Table 10 classifies these failure modes into four types, labeled from Mode A through Mode D (Figure 13). Principals of use and issues corresponding to application of pull-off test are comprehensively discussed in technical literature (Austin et al., 1995; Bakhsh, 2010; Bonaldo et al., 2005; Bungey & Madandoust, 1992; Chmielewska et al., 2003; Cleland & Long, 1997).

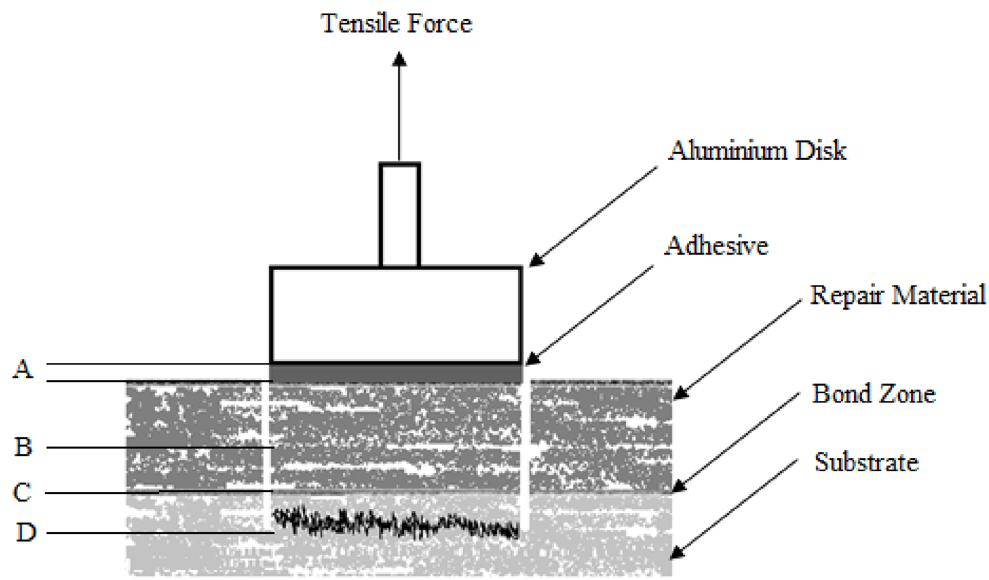


Figure 12. Schematic representation of pull-off test principle

Table 10. Pull- off failure types

Failure Mode	Failure Mode	Causes of Failure
A	Adhesive failure	Improper adhesive bonding. Not an acceptable failure mode.
B	Repair material failure	Not a proper failure. Deteriorated repair material.
C	Bond Failure	Weak bonding. provides an actual measurement of the bond strength
D	Concrete substrate failure	Proper bonding.

The tensile pull-off strength (S_{PO}) is defined as pull-off force (F_T) divided by the area of the fracture surface (A_f):

$$S_{PO} = \frac{F_T}{A_f} \tag{4}$$

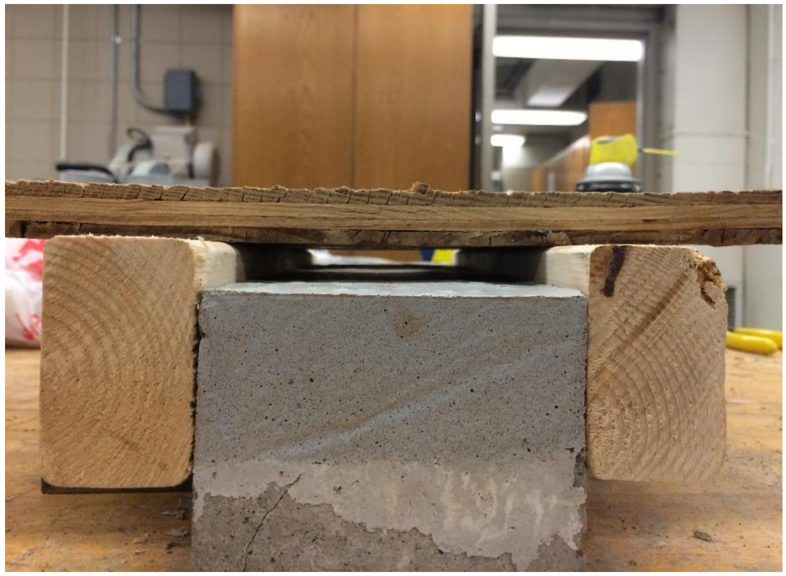
All F-T samples after 300 freezing and thawing cycles were subjected to pull-off tests to investigate the influence of freezing and thawing on the bond strength of the repair materials. The pull-off test was conducted in accordance to ASTM C1583 (ASTM C1583-13, 2013). The test procedure starts with a preparation of the test area. The test follows by partial coring into the existing substrate, in the perpendicular direction to the repair surface. A Milwaukee Dymodrill 4096 with a two inch (50 mm) diameter core barrel was applied for partial depth coring (Figure 14). Two cores were conducted on each specimen and therefore in the best case, six pull-off values could be measured for each set of material. After coring, as can be observed in Figure 15, a metal disc was attached to the core using a high strength epoxy. For this purpose a 24 hour curing period was needed. However, depending on the environmental condition and adhesive properties, other periods of time might be used.

Finally, since the width of the specimens was less than the required dimension for conducting the pull-off test, a testing frame was set up and the pull-off test was performed.

Figure 13. Coring process

Figure 14. Attaching pull-off disks

Figure 16 and Figure 17 show the test setup and the pull-off tester. A James Bond Test ™ MK III was used to apply tension to the disks until failure. Average of maximum strengths was recorded, and failure modes were reported.



(a)

(b)

Figure 15. Pull-off testing setup

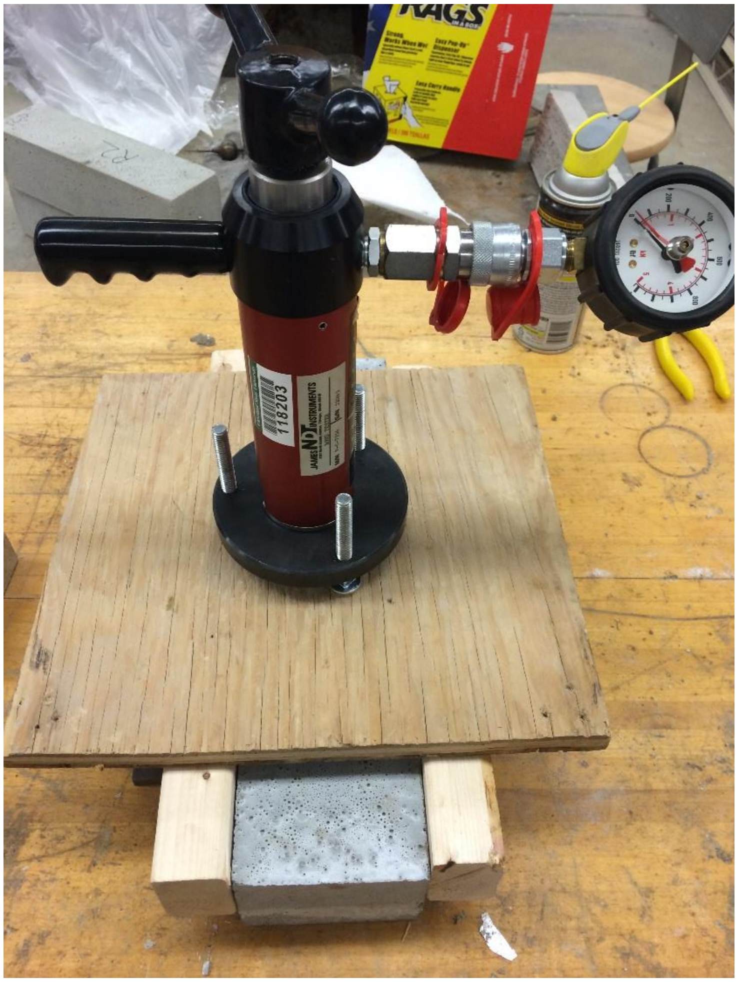


Figure 16. James bond pull-off tester

Shrinkage

The length measurement of specimens was started immediately after removing their molds and then continued up to 180 days. Figure 12 shows the test specimens and the shrinkage testing setup.

(a)

(b)

Figure 17. (a) Shrinkage Specimens, (b) Shrinkage testing and setup

Two hours after casting the materials, the specimens were removed from the steel molds. Then, the specimens were stored in a room with constant temperature of 73 °F ± 5 (23 ± 2 ^{o}C) and relative humidity of 35% for shrinkage deformation measurement. The length change measurement were conducted in the 1st, 2nd, 3rd, 5th and the 7th day of the first week, subsequent length change measurements were conducted every 7 days up to 28 days, and then every month up to 180 days.

Compressive Strength

The compressive strength of the repair material samples was measured according to ASTM C 39 (ASTM C39-15, 2015) after 3hours, 1 day, and 7 days. Three cylinder samples were prepared through for each specific day and measured for compression and their average was calculated.

All experiments were conducted in laboratory under constant conditions of air temperature of 73 °F ± 5 (23 °C $\pm$ 2) and relative humidity 60%.

CHAPTER V

RESULTS AND DISCUSSION

This experimental program was the last of three phases of the overall research project sponsored by the Ohio Department of Transportation (ODOT), under a research contract titled "Evaluation of High Performance Pavement and Bridge Deck Wearing Surface Repair Materials", State Job number 124816, Agreement number 25969. The first phase was focused on the technical literature to find the best repair materials that can withstand the severe environmental condition specified by ODOT district 8. Phase two of this research project was concentrated on the field evaluation of the selected repair materials. This study (phase three) is generally focused on the laboratory assessment of the repair materials. Moreover, it attempted to make adequate comparisons between the field and the laboratory results to facilitate the selection of the best repair material for concrete pavement and bridge deck repair purposes.

The type, number, and selection method of the repair materials have been explained comprehensively in chapter 3. Six of the materials (FlexSet, MG-Krete, Delpatch, Repcone 928, Quikrete, and SR2000) were selected to be evaluated both in the field and in the lab. The obtained results for these repair materials are presented and analyzed in phase I of this chapter. Two of the materials (Pavesaver and Pavemend SLQ) were selected to be evaluated as already failed products (reported by ERDC (2011) and/or NPTEP (2008)), which are discussed in phase II of this chapter. The raw values of the obtained results from the laboratory evaluations are illustrated in Appendix A through Appendix F.

Further, the mixing methods, casting procedure, specimen preparation, and conducted tests have been thoroughly described in Chapter 4.

Phase I

Freeze-Thaw (Resonant Frequency, UPV, mass change, and scaling damage)

The freeze-thaw durability of concrete is typically expressed by a durability factor (DF). Table 11 tabulates the DF (%) of the investigated materials after each 30 F-T cycles interval. Figure 18 illustrates the DF (%) of the composite samples calculated for cycle number at which the composite material was debonded, or when the relative dynamic elastic modulus is less than 60%. As can be observed in Table 11, Delpatch is the only material that debonded after 90 F-T cycles. Therefore, except for Delpatch, DF of the repair materials shown in Figure 18 was calculated after 300 F-T cycles. Theoretically, the durability factor should not be more than 100%. However, it can be seen from the figure that most of the materials finished over 100, which indicates the soundness of the materials after 300 cycles. Delpatch exhibited the least DF of 13 compared to the other investigated materials.

Table 11. Durability factor (DF) of the repair materials

Materials	F-T cycles									
	30	60	90	120	150	180	210	240	270	300
MG-Krete	12	25	35	51	61	73	85	97	112	129
Repcon 928	11	22	37	50	64	75	86	99	111	123
FlexSet	10	20	31	40	49	65	76	91	107	109
SR2000	11	22	25	32	40	46	54	61	69	77
Quikrete	12	24	35	50	56	66	72	81	88	96
Delpatch	15	23	13	Debonded						

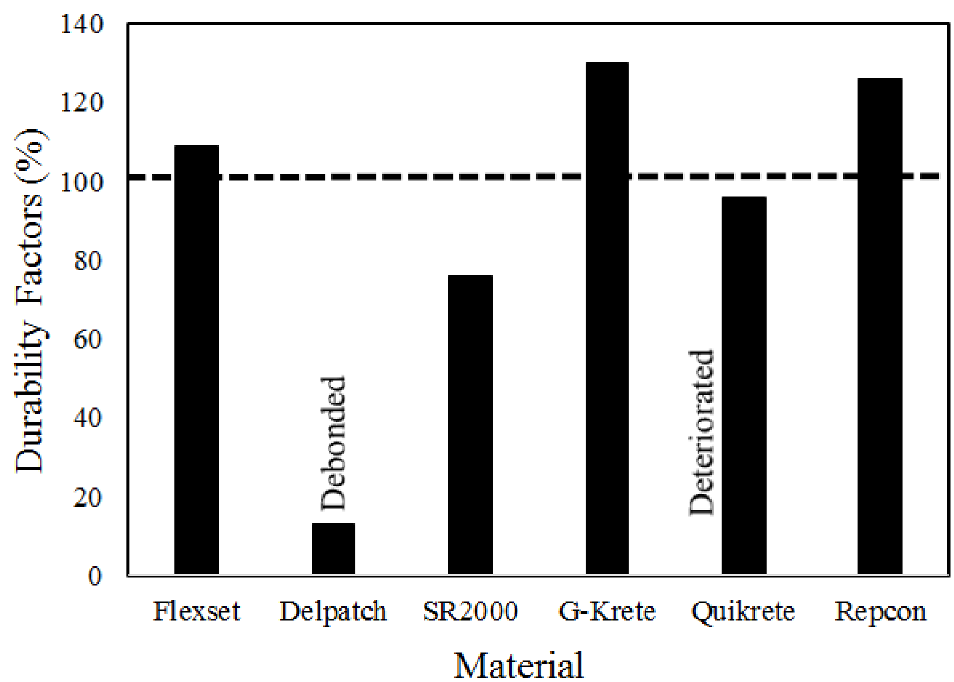


Figure 18. Durability factor of the repair materials after 300 cycles

Figure 19 and Figure 20 demonstrate the fundamental transverse frequency (TF) and Ultrasonic Pulse Velocity (UPV) evolution of the investigated repair materials subjected to F-T cycles, respectively. As can be seen in the Figure 19, except for FlexSet, all repair materials experience a slight increase between the two initial measured TF values. In addition of the saturation of the samples exposed to F-T cycles, this increment can be due to the continuation of the hydration (Prem Prabhat, Bharatkumar B, 2013). It can be seen that Delpatch is the only material experiencing an instantaneous drop in TF values after 60 cycles of F-T. This is attributed to the fact that bonding between Delpatch and the substrate was extremely weakened after almost 60 F-T cycles. It can be seen in Figure 20 that generally, the velocity of ultrasonic waves through the composite samples is higher for the non-polymeric repair materials. This is due to the higher density of non-polymeric materials.

The UPV value of all the repair materials, except for FlexSet, is reduced (Figure 20). The reduction in the velocity is attributed to the internal damage through the composite samples. In both Figures (Figure 19 and Figure 20), the lowest values belong to the polymeric repair material types (FlexSet, Delpatch, and SR2000). The field results confirm that these tests are not suitable when greater thicknesses are taken into consideration, since no values could be recorded for these types of material on the field. This can be attributed to different parameters. One is due to the elastic properties of the materials. Generally, a rigid material is considered of atoms and molecules with robust forces of attraction between them. These forces of attraction control how fast the particles return to their primary positions, when unloaded. Particles that return to their resting position faster can vibrate at higher speeds. In other words, waves can propagate faster through materials with higher elasticity (like concrete) than it can travel through materials with lower elastic properties.

Therefore, at a particular level, the thickness of high flexible materials may avoid the waves from traveling through the whole thickness. Another can be because of damping properties of the polymeric materials. Damping is an influence within an oscillatory system and causes reduction, restriction or prevention of its oscillations. Therefore, damping properties of the material reduces the frequency of the waves and depending on the depth of the repair, UPV may or may not be measured.

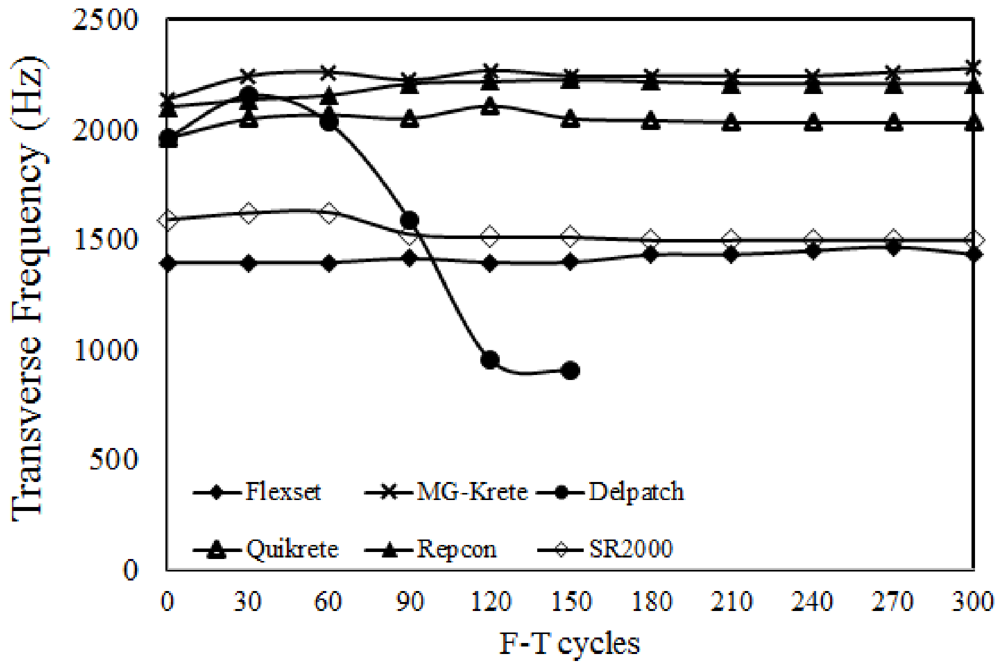


Figure 19. Fundamental transverse frequency of composite samples subjected to F-T cycles

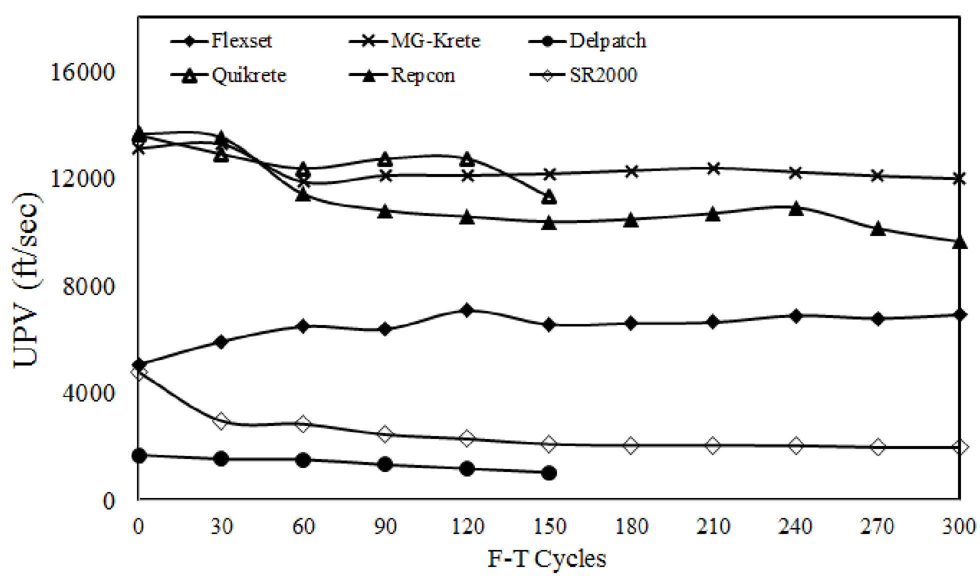


Figure 20. Ultrasonic Pulse Velocity of the Composite Samples Subjected to F-T Cycles

In order to evaluate the scaling damage of the composite samples, visual inspection of the composites subjected to F-T cycle is demonstrated in Figure 21. The first Delpatch specimen debonded after 90 cycles and the second one debonded after 120 cycles. However, the third Delpatch specimen remained mostly intact at 300 cycles, although it was partially debonded from the substrate (Figure 21). Delpatch composites almost performed well in other investigated aspects of durability. In case of Repcon 298, as can be seen in the figure, large flakes began to appear on the surface of Repcon repair material after 90 cycles. In addition, noticeable edge damage was visible for Quikrete material after 120 cycles. Table 12 lists the visually rated Scaling damage of the repair materials based on Table 9. It can be seen that no signs of deterioration was observed for any of the repair material for the first 30 cycles. The results of visual scaling damage confirm the previous results achieved in this study.

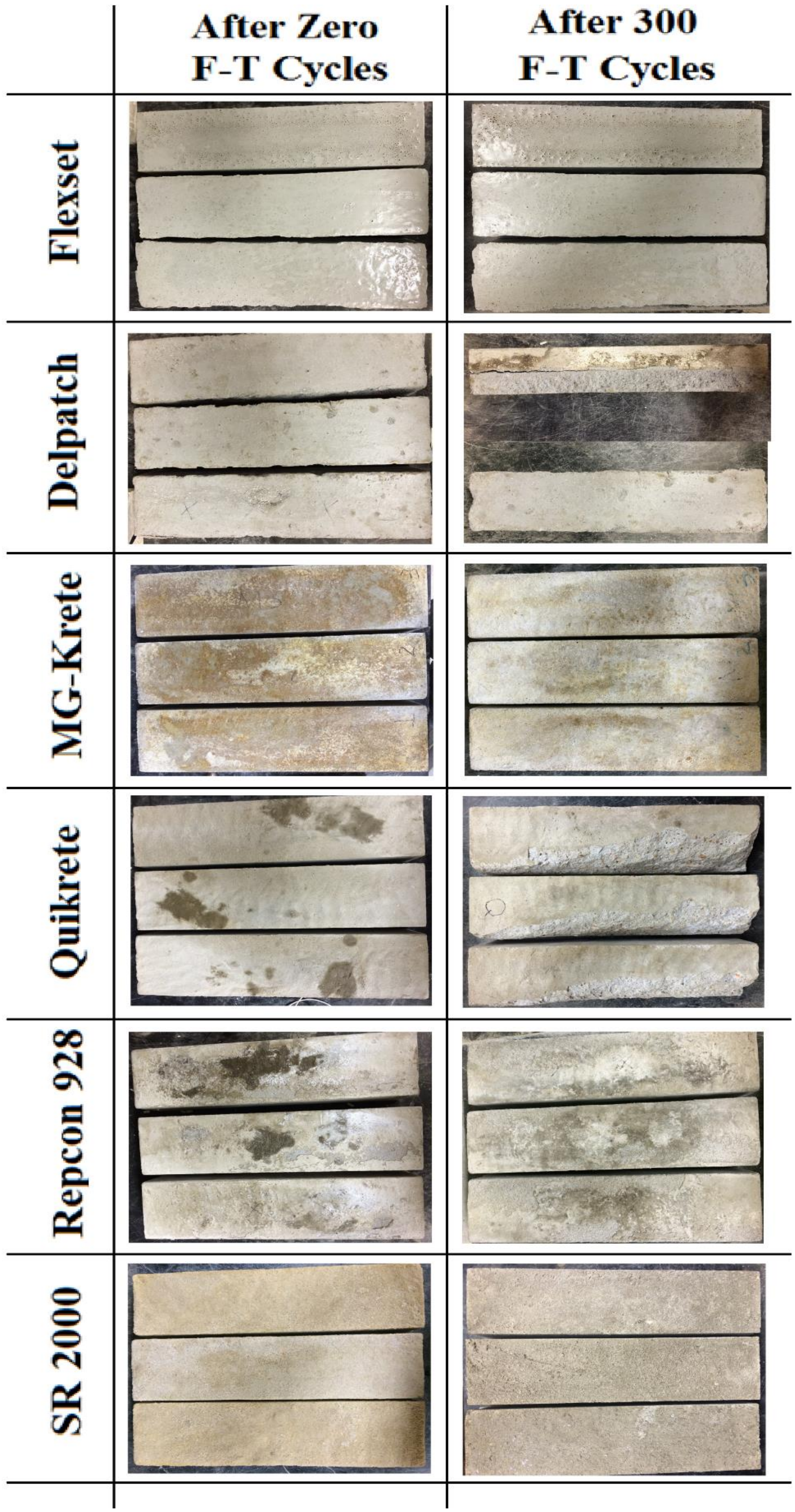


Figure 21. Visual Inspection of Composite Samples subjected to F-T cycles (Scaling Damage)

Table 12. Scaling damage rating of the composite materials subjected to F-T cycles

Material	F-T Cycle										
	0	30	60	90	120	150	180	210	240	270	300
FlexSet	0	0	0	0	0	0	0	0	0	0	0
Delpatch	0	0	3	5	5	5	5	5	5	5	5
SR2000	0	0	0	0	0	0	0	0	0	0	0
MG-Krete	0	0	0	0	0	0	0	0	0	0	0
Repcon	0	0	2	2	2	2	2	2	2	2	2
Quikrete	0	0	0	3	3	4	4	5	5	5	5

According to ASTM C666, the Freeze-Thaw test is mainly to investigate the dynamic modulus of elasticity and mass change of the samples imposed to freezing and thawing cycles. Formation of microcracks has reducing effects on the Pc (Relative Dynamic modulus) values of the material. In addition, mass reduction of the specimens shows the degradation of the material (Prem Prabhat, Bharatkumar B, 2013).

Figure 22 shows the Pc (RDM) of the composite samples considering that the initial transverse frequency is at 30 cycles. It is worth noting that the Pc is a measure of the current dynamic modulus compared to the initial dynamic modulus of the material and is not an exact indicator of the true dynamic modulus of the materials. Calculation of Pc is based on the assumption that the weight and dimensions of the specimen remain constant throughout the test, which is not true in many cases due to disintegration of the specimen. However, if the test is to be used to make comparisons between the RDM of different specimens, Pc as defined is adequate for the purpose (ASTM C666-03, 2008). The dashed line is the limited Pc value (60%) defined by ASTM C666. It indicates the materials with Pc value of less than 60% are suffering from severe deterioration. It can be seen that all specimens, except Delpatch and SR 2000 exhibit the same or higher Pc values than at the beginning of testing indicating that the samples are still internally sound. The low recorded Pc value for Delpatch composites after 90 F-T cycles is mostly due to debonding of the layers. No value could be recorded for Delpatch after 150 F-T cycles.

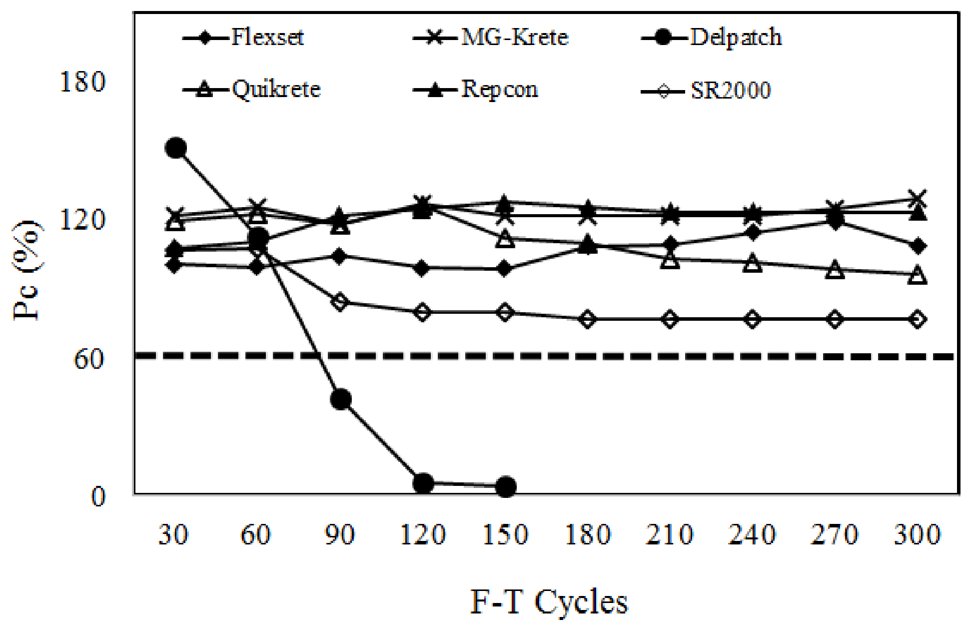


Figure 22. Relative Dynamic Modulus of Composite Samples subjected to F-T

Figure 23 illustrates the weight loss variation of the composite samples subjected to freeze-thaw cycles. The slight increase between the two first measurements is due to the dry condition of the initial measurements, while the specimens were saturated in the following measurements. It can be observed from the figures that weight loss measurement does not directly correlate with the Pc change for the same number of cycles. Some materials lost mass while maintaining constant Pc, and vice versa. For example, the Quikrete material showed the highest weight lost among the investigated materials (see Figure 23), while after 300 F-T cycles, the composite materials made with Quikrete are still revealing an acceptable value for Pc. Alternatively, specimens made with Delpatch show that Pc is reduced from 151% to about 4%, while there is only about 4% mass change.

Thus, it can be concluded that the evaluation of material durability only based on Pc might be inadequate and the weight loss of the materials is an important parameter to be considered when investigating the repair materials.

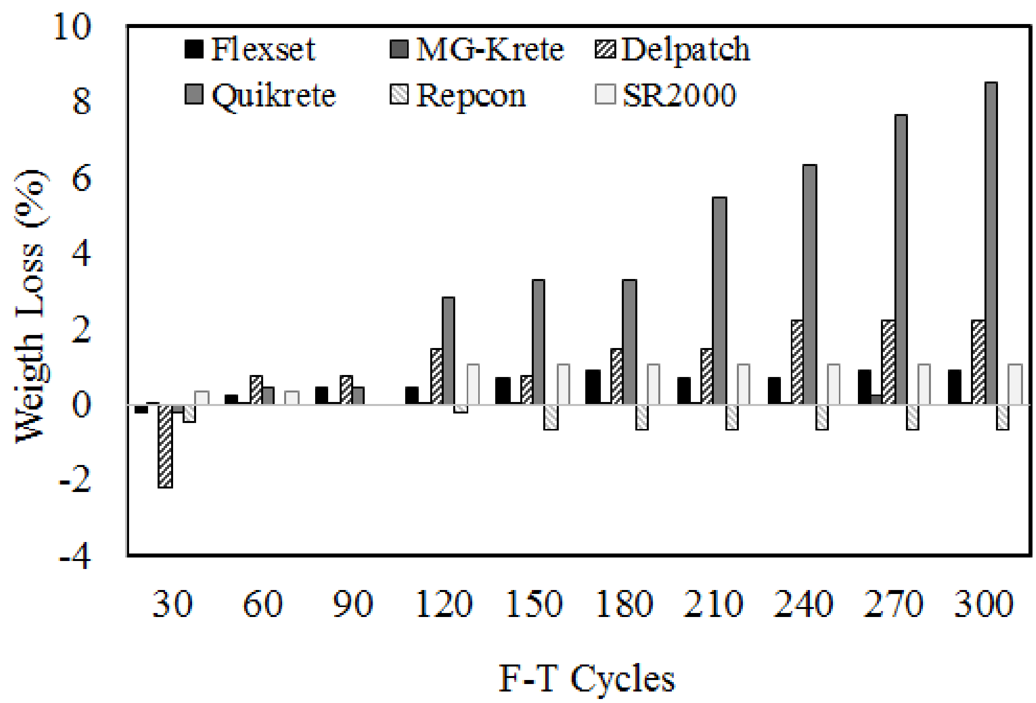


Figure 23. Weight loss of the composite samples subjected to F-T cycles

Pull-Off

Eventually, F-T samples after 300 freezing and thawing cycles were subjected to the pull-off test. A Steel wire brush was used to ensure that all the cores are free of grease and dust. Table 13 tabulates the pull-off test results. There is a considerable scatter in the measured bond strengths. This is because of the variable nature of bond, and in part due to testing (Delatte et al., 2001). As mentioned in Table 10, there are four different modes that a pull-off specimen might have failed. For most of the cores, FlexSet, Repcon 928, and Quikrete exhibited failure mode C. This is the only failure mode that offers an actual evaluation of the bond strength between the repair materials and the substrate (Figure 24).

Since in other failure modes the bond does not fail and remains intact, the others offer a lower bound measurement. SR2000 exhibited failure mode B for most of the cores, in which a small part of the surface was fractured at a very low tensile stress of 45 psi (Figure 25). In case of MG-Krete, failure mode B and D were occurred at a high tensile stress of 452 psi.

Table 13. Pull-off test results

Core Number	Bond Strength of repair materials in psi (failure mode)					
	FlexSet	Delpatch	SR2000	MG-Krete	Repcon 928	Quikrete
1	80 (C)	0	92 (C)	516 (D)	400 (B)	228 (C)
2	76 (C)	0	32 (B)	528 (D)	480 (C)	304 (C)
3	88 (C)	0	52 (B)	448 (B)	480 (C)	-
4	56 (C)	0	16 (B)	432 (B)	372 (C)	-
5	68 (C)	0	36 (B)	400 (B)	448 (C)	-
6	64 (C)	0	40 (B)	392 (B)	400 (C)	-
Average bond strength (psi)	72	0	45	452	430	266

Note: 1 psi = 0.0069 Mpa

Figure 24. Repcon 928 specimen after pull-off testing

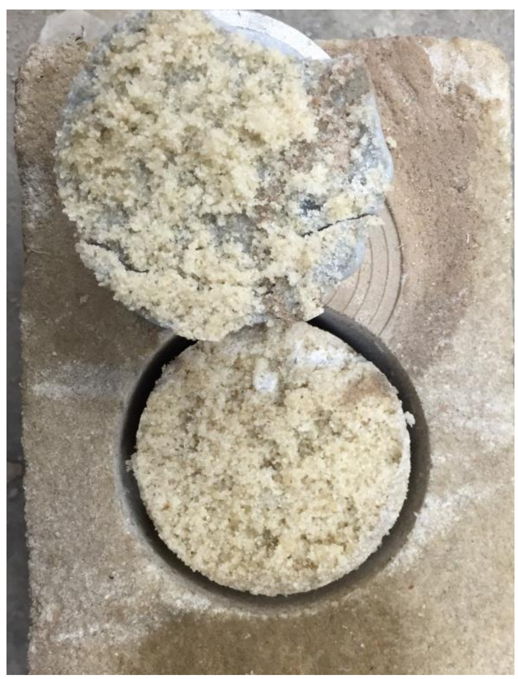


Figure 25. SR2000 specimen after pull-off testing

The bonding of the composite specimens was also visually inspected (Figure 26). As it is shown in figure 26, no sign was observed that suggests concern for failure.

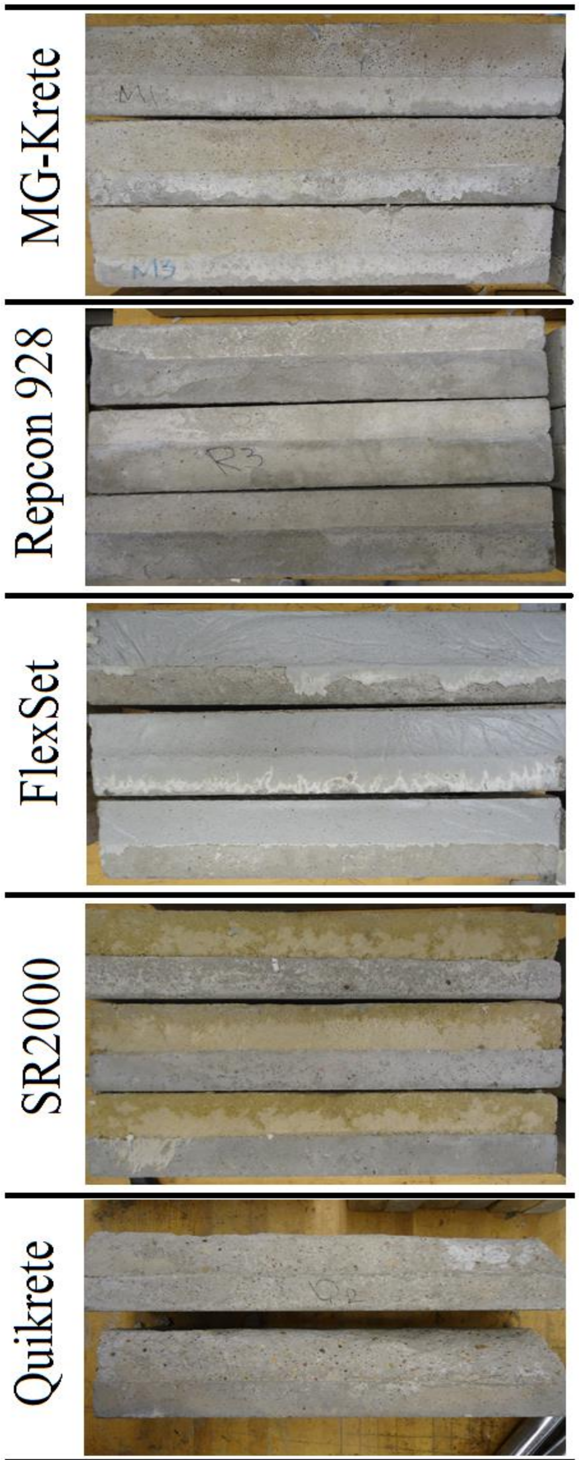


Figure 26. Visual inspection of bonding

Shrinkage

Figure 27 plots the shrinkage evolution of the repair materials. As can be seen in Figure 27a, the FlexSet exhibited an obvious greater shrinkage, more than 20 times as much, than the other repair materials (Delpatch, SR2000, MG-Krete, Repcon 928, and Quikrete), therefore, it is shown in a separate plot to provide a better comparison of the other shrinkage. Figure 28 presents the shrinkage of the investigated repair materials after 7 and 56 days. In addition, Figure 29 shows the length change of the repair materials at day 28. Among all the investigated repair materials, MG-Krete exhibited the lowest shrinkage (Figure 27 and Figure 28). ASTM C928 specifies 0.15% of length change in air to be the maximum acceptable shrinkage value for the patching materials. As can be seen in Figure 29, FlexSet, SR2000, Quikrete are failing this criterion.

It is well recognized that drying shrinkage is a result of the loss of water around cement capillary pores (Güneyisi, Gesoğlu, & Özbay, 2010). Besides, using basic knowledge of material technology, there is a well-recognized relationship between the porosity and elasticity modulus of concrete. Hwang and Khayat (Hwang & Khayat, 2010) indicated that mixes having higher elastic modulus are more rigid and so, less porous. Therefore, materials with higher modulus of elasticity undergo less shrinkage compared to those with lower elastic modulus. The results of this study, however, show that this conclusion is marginal. For example, although Delpatch has the lowest Pc value (Figure 22), it is exhibiting low shrinkage.

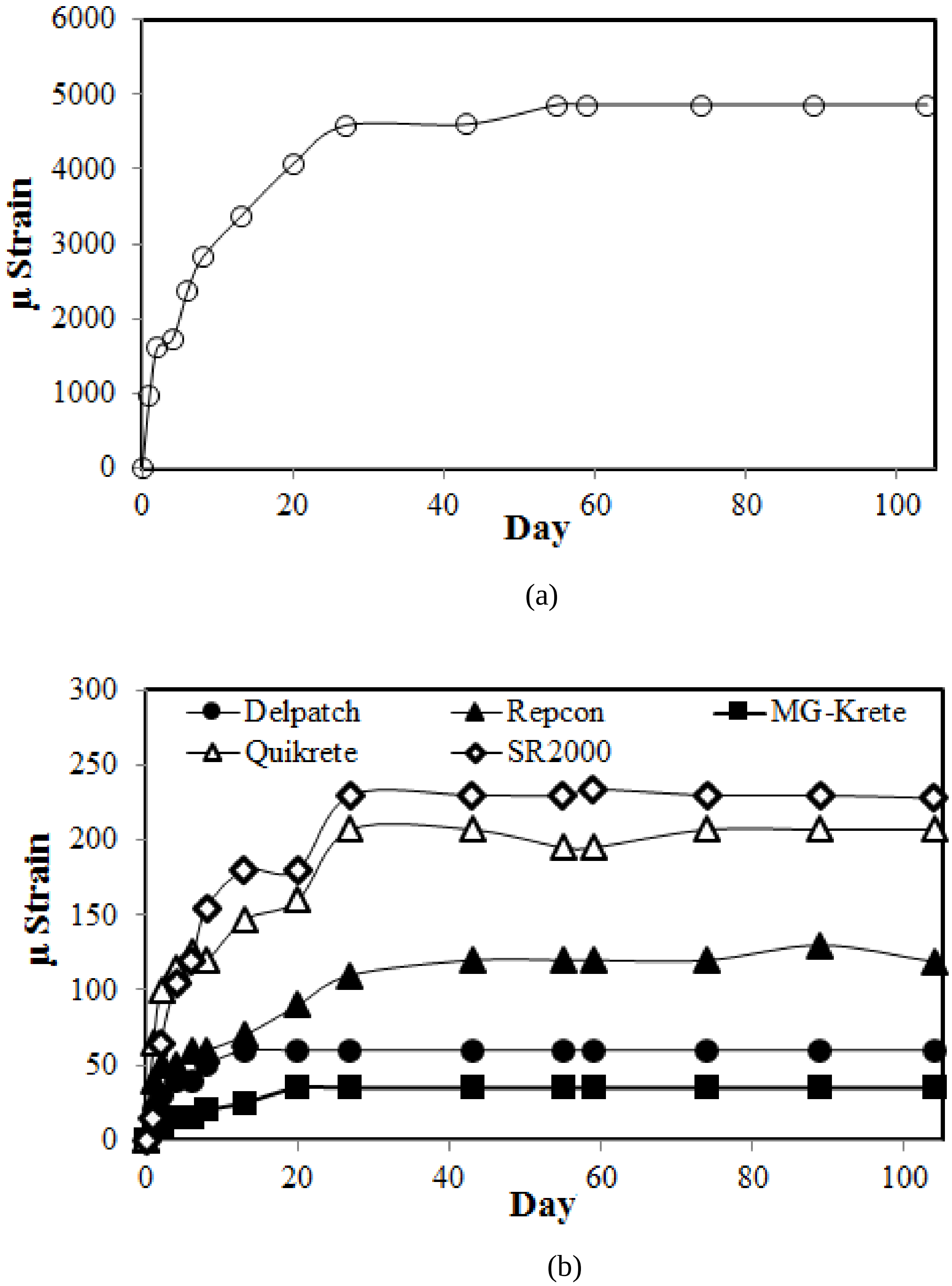


Figure 27. Shrinkage evolution of the repair materials (a) FlexSet, (b) Other repair materials

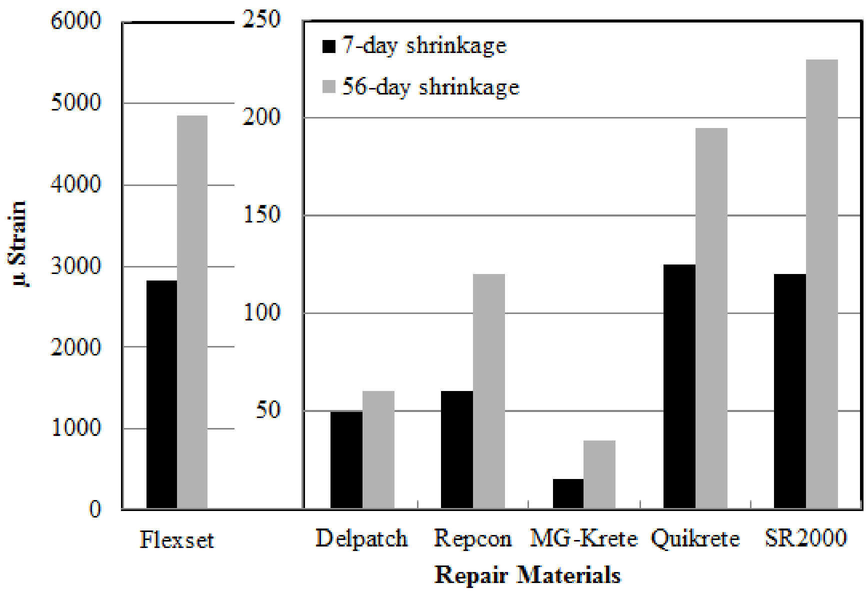


Figure 28. Shrinkage of the repair materials at 7 and 56 days

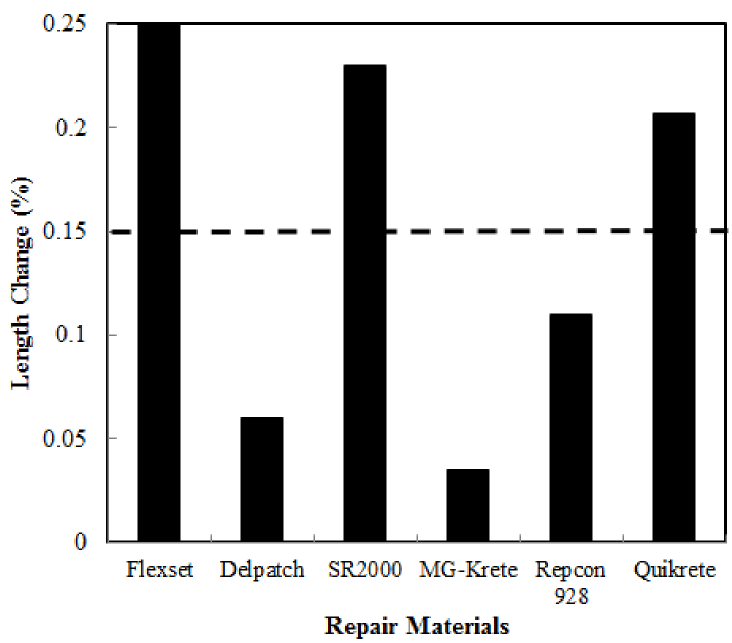


Figure 29. Length change at 28 days in air

Compressive Strength

Figure 30 presents compressive strength of the repair materials after 3 hours, 1-day and 7-days of casting and compressive strength of the based materials after 7 and 28 days. It was not possible to measure the compressive strength of the polymeric repair materials (FlexSet, Delpatch, and SR2000) due to their high flexibility. As can be seen in Figure 31, polymeric materials under compression deform visibly, and once they are unloaded, the specimen expands. Therefore, as these materials are not brittle, no compressive strength was able to be measured. The highest measured early 3 hours strength of 3000 psi (20 Mpa) among repair materials belongs to MG-Krete. The X points in the figure designate the corresponding values reported by the producers. MG-Krete exhibited relatively close values to what the manufacturer reported. It can be seen that the substrate concrete meets the requirement of 4500 psi (30 Mpa) after 28 days of curing.

To check the compatibility of the repair materials with the substrate, compressive strength becomes important as it contributes to the stress distribution during the loading time. Therefore, in case of compatibility, among the investigated repair materials, MG-Krete seems to be the most compatible repair material when only compressive strength is taken into consideration, since its compressive strength is comparable to that of the substrate.

Eventually, this is important to take note that the patching materials that have very rapid strength, hydrate more quickly and therefore develop a weaker bond matrix (Dave, Dailey, & Eric, 2014). Therefore, the ultimate compressive strength of the composite material would be lower than the expected values. This can be misleading when compressive strength is considered as a measure of the quality of a patching material. A patch material that reaches a compressive strength sufficient to support traffic is the goal.

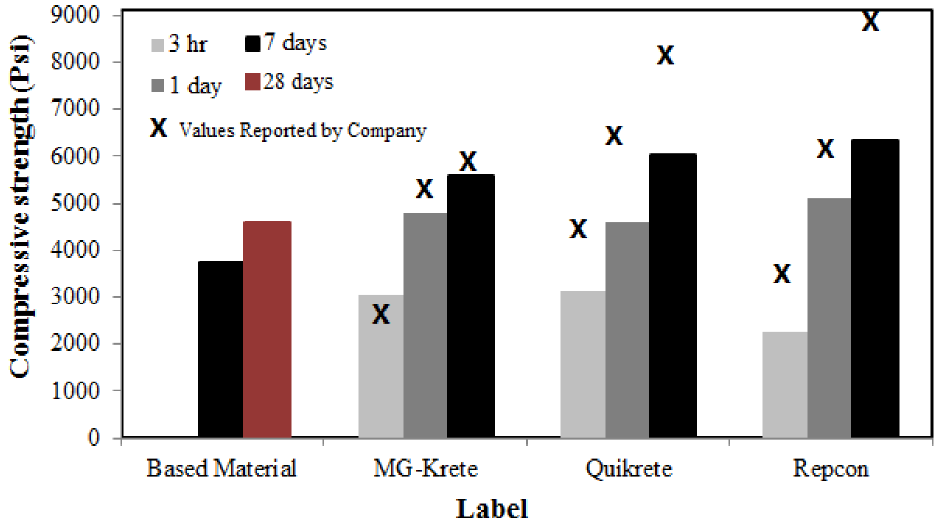


Figure 30. Compressive strength of the repair materials.

Note: 1 psi = 0.0069 Mpa

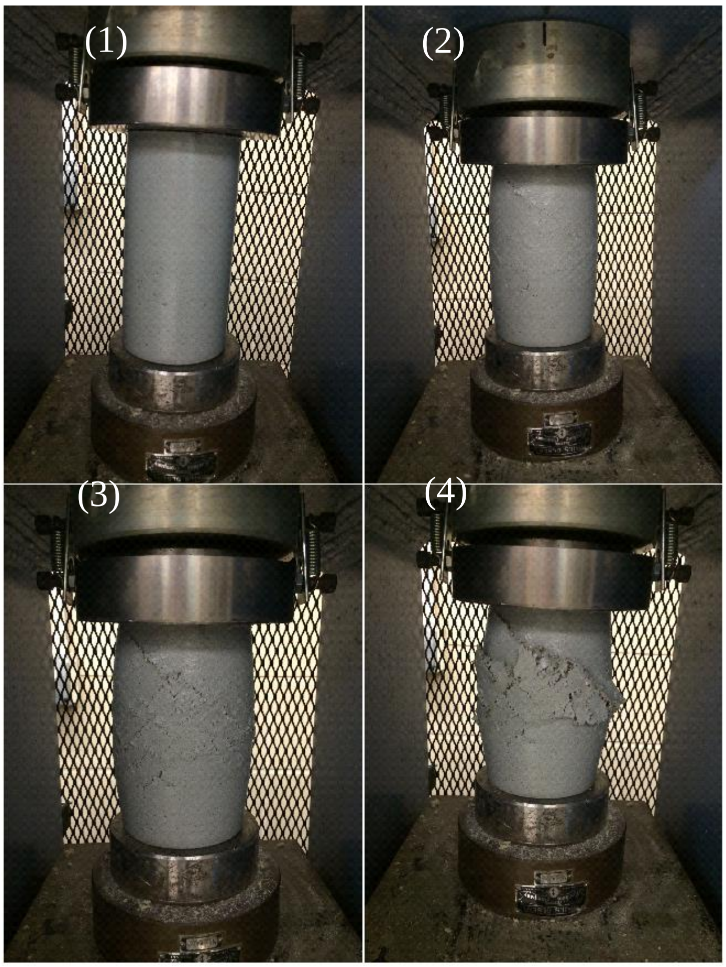


Figure 31. FlexSet cylinders under compression

Phase II

This section presents the results obtained through the laboratory investigation for the two already disapproved repair materials (Pavesaver and Pavemend SLQ). One of the Pavemend SLQ's F-T specimens was debonded after 150 freezing and thawing cycles. However, the other two specimens did not exhibit any sign of scaling through the scaling damage rating evaluation. Pavesaver specimens also exhibited a scaling damage rating of zero after 300 F-T cycles.

Table 14 tabulates the durability factors calculated for the products throughout the freezing and thawing cycles. As can be observed in the table, regardless of the debonded specimen, durability factor of both repair materials finished over 100%, which indicates the soundness of the materials after 300 F-T cycles.

Table 14. Durability factor (DF) of the repair materials

Materials	F-T cycles									
	30	60	90	120	150	180	210	240	270	300
Pavesaver	11	21	33	45	52	63	73	84	94	105
Pavemend SLQ	11	23	36	47	59	71	83	95	107	118

Figure 32 and 33 demonstrate the transverse frequency (TF) and UPV evolution of the products, respectively. As can be seen in Figure 32, both repair materials experience a slight increase between the two initial measured TF values that can be due to the continuation of the hydration (Prem Prabhat, Bharatkumar B, 2013). The UPV value of both products is slightly reduced (Figure 33). The reduction in the velocity is attributed to the internal damage through the composite samples.

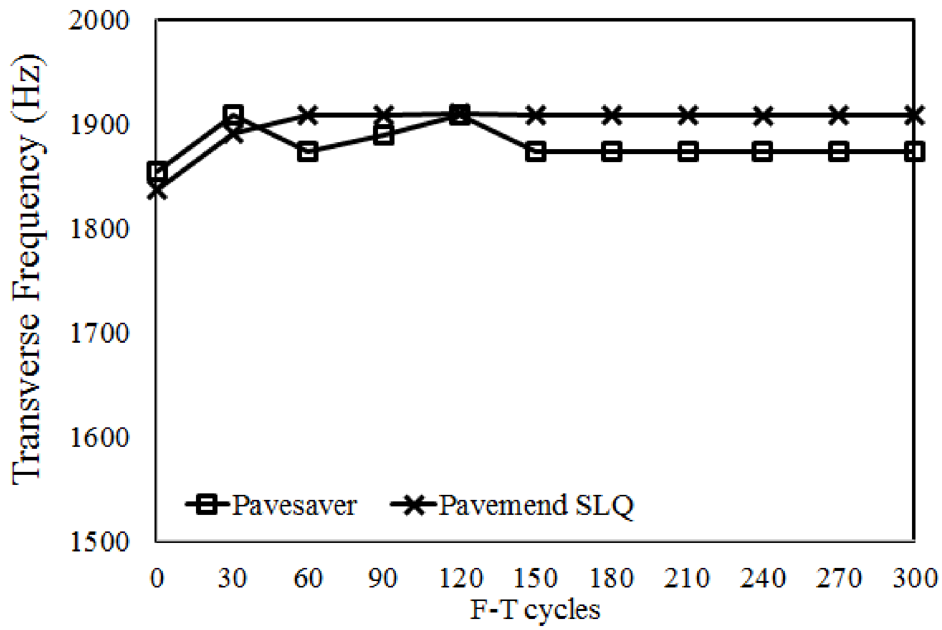


Figure 32. Fundamental transverse frequency of composite samples subjected to F-T cycles

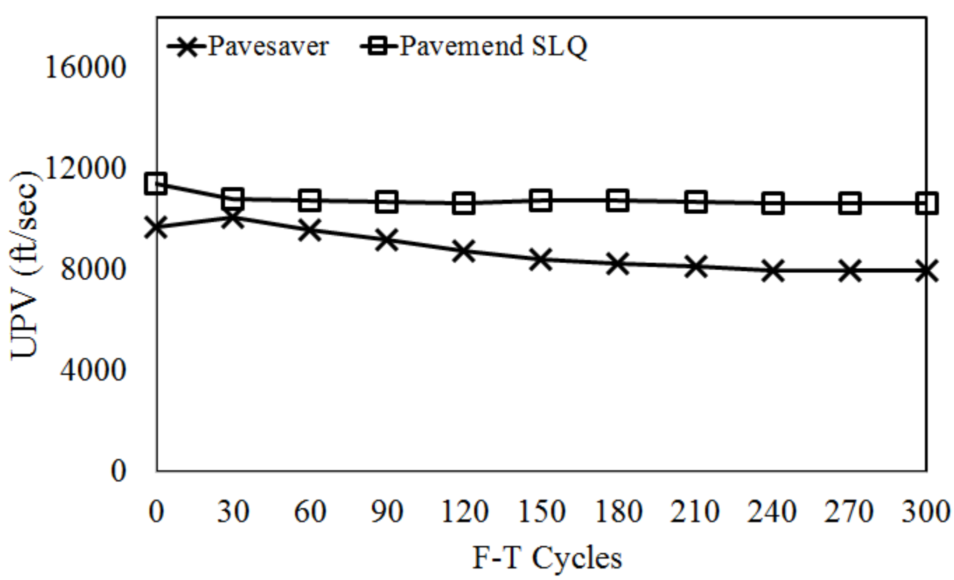


Figure 33. Ultrasonic Pulse Velocity of the Composite Samples Subjected to F-T Cycles

Figure 34 shows the Pc (RDM) of the composite samples considering that the initial transverse frequency is at 30 cycles. As mentioned before, the dashed line is the limited Pc value (60%) defined by ASTM C666. It indicates the materials with Pc value of less than 60% are suffering from severe deterioration. It can be seen that both products, exhibited the same or higher Pc values than at the beginning of testing indicating that the samples are still internally sound.

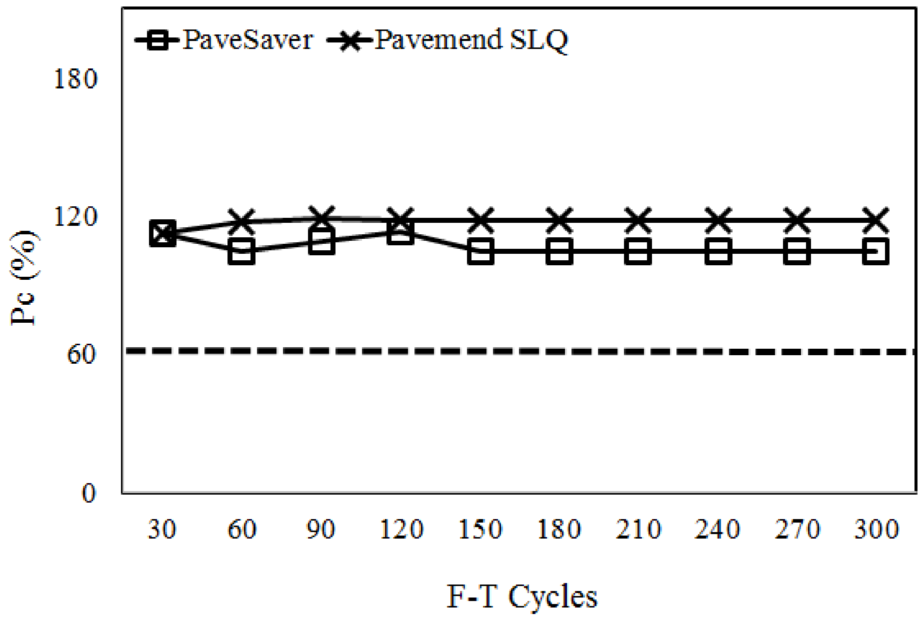


Figure 34. Relative Dynamic Modulus of Composite Samples subjected to F-T

Figure 35 illustrates the weight loss variation of the composite samples subjected to freeze-thaw cycles. The slight increase between the two first measurements is due to the dry condition of the first measurement, while the specimens were saturated for the next evaluations. It can be seen that none of the materials exhibited mass loss throughout the F-T cycles.

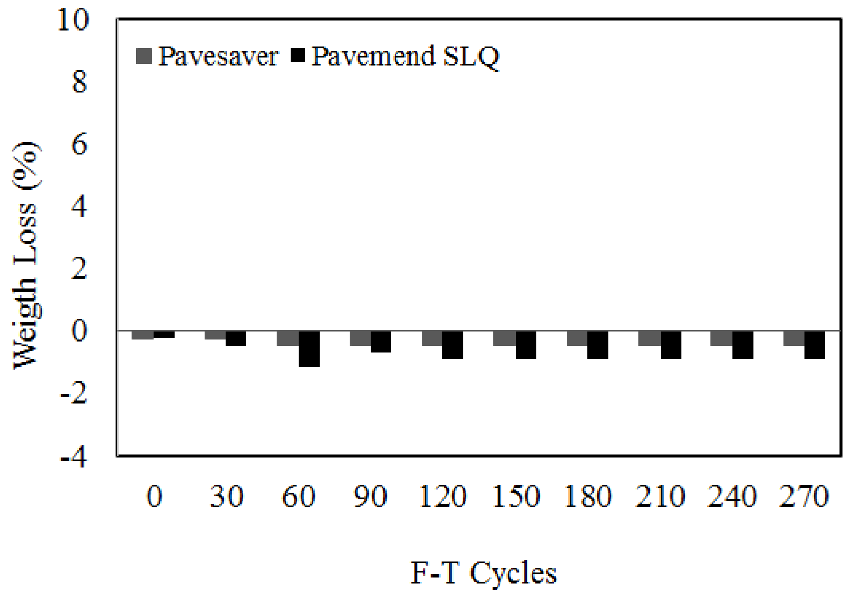


Figure 35. Weight Loss of the Composite Samples subjected to F-T cycles

After 300 F-T cycles, specimens were prepared for the pull-off testing. Table 15 shows the pull-off test results. It can be observed that most of the cores exhibited failure mode C, which is the only reliable failure mode to evaluate the exact bond strength between the repair materials and the substrate. Generally, the Pavesaver exhibited higher bond strength compared to the Pavemend SLQ. In case of the Pavemend SLQ, one of the F-T specimens was debonded after 150 freezing and thawing cycles. Besides, two cores were debonded while the coring was conducting.

Table 15. Pull-off test results

	Bond Strength of repair materials in psi (failure mode)						Average
Core Number	1	2	3	4	5	6	(psi)
Pavesaver	192 (C)	160 (C)	208 (C)	200 (C)	(A)	(A)	190
Pavemend SLQ	64 (C)	60 (C)	Debonded during coring		0	0	62

Note: 1 psi = 0.0069 Mpa

Figure 36 shows the length change evolution of the repair materials. It can be seen that Pavesaver exhibited much less shrinkage value compared to Pavemend SLQ. The length change values of Pavesaver and Pavemend SLQ after 28 days were 0.075 and 0.195 %, respectively. Based on the criterion specified by ASTM C928, maximum acceptable shrinkage value for the repair materials is 0.15% of length change. Therefore, Pavemend SLQ failed this requirement.

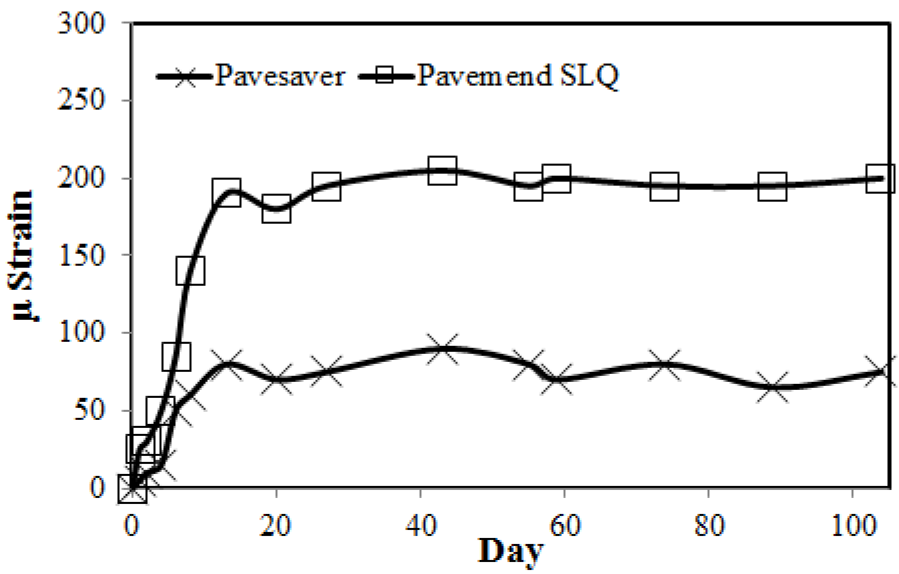


Figure 36. Shrinkage evolution of the repair materials

It was not possible to measure the compressive strength of the Pavesaver repair material, similar to the other polymeric repair materials investigated in this study (FlexSet, Delpatch, and SR2000). Table 16 shows the compressive strength measured for the Pavemend SLQ repair material and those reported by the manufacturer. It can be seen that except for the 3hour measurement, Pavemend SLQ exhibited similar or higher compressive strength compared to those reported by the producer.

Table 16. Compressive strength of Pavemend SLQ

Age	Compressive Strength (psi)		
	3 hr	1 Day	7 Day
Lab	2660	4704	5388
Reported by manufacturer	>3000	>4500	>5000

Note: 1 psi = 0.0069 Mpa

CHAPTER VI

PERFORMANCE REVIEW OF PRODUCTS

This study was conducted to determine which products possess these specifications before acceptance as patching repair materials. The following is brief discussion on the patch inspection in the field, which were gathered by Lesak (2014) and then compared with test results in the laboratory. The list of materials mentioned here is alphabetically tabulated and is in not reflected by any ranking system.

Patch Inspections

As of August of 2014, two patch inspections have been completed for this project. On May 29, 2014, a preliminary inspection was performed on the 14 winter patches installed in March of 2014. A month after the summer patch installation, on July 30, 2014, another inspection was performed on all of the 85 installed patches for this project. With the help of ODOT traffic control, a visual inspection, and delamination testing was performed during both inspections. The delamination test was performed with the use of a piece of rebar for the first inspection, and the Delam 2000 for the second inspection. For the rebar test (ASTM D4580-12, 2012), a 4 to 5 foot long piece of rebar was used to tap on the patch to check for potential debonding and/or delamination. When hitting the patch that is sound and bonded well to the pavement, the rebar makes a distinct ping. While it makes more of a thudding noise if the patch is not bonded well, or is deteriorated. The second method is very similar to the rebar test. However, uses a multi-toothed and rotating apparatus instead of the piece of rebar. The Delam 2000 was rolled over the patches, making a consistent ringing sound if the patch was sound. While it makes a hollow sound over a deterriorated section of patch or pavement. The results and observations from this inspection will be discussed in this chapter

Delpatch

The Delpatch installed patches did not have any visual cracks or distress as of the July inspection. These patches also passed the delamination test, and showed no signs of concern for possible failure (scaling damage rating: 0).

FastSet DOT Mix (Quikrete)

The Quikrete repair areas had two patches with cracks through them (scaling damage rating: 1). These cracks were small and expected, and were formed by cracks already present in the concrete pavement in which the patches were placed. The crack in the pavement around on of the patches can be seen on the right side of the patch in Figure 37, but the crack through the patch following the crack through the pavement is difficult to see, as it is not very wide. The Quikrete patches also passed the delamination test, and showed no signs that would suggest concern for possible failure.

Figure 37: Quikrete Patch with a small crack through the patch

FlexSet

Overall, the FlexSet patches appeared sound and intact after both inspections. The only visible sign of distress was that three of the eight FlexSet patches had small surface spalling (Figure 38) (scaling damage rating: 1). The figure shows a picture of a patch from the first inspection. The second inspection did not show the spalling area increase much, compared to the first inspection, for all three of the patches that showed spalling. None of the new patches showed spalling during the second inspection.


E

Figure 38. FlexSet Patch with Spalling

The rebar test, which was performed on the FlexSet patches during the first inspection, gave primarily good results on all of the patches. However, in some cases, an inconsistent noise was produced from the rebar test on a small area of both of the patches. Figure 39 shows the rebar test being performed on one of the patch, with the rebar pointing to the area that failed the rebar test. During summer installations, June, the delamination test was performed on patches, using the Delam 2000. No delamination or debonding seemed to be present, as of the July inspection, at any of the FlexSet patches. The Delam 2000 was used on all of the Flex Set patches during the second inspection, and all of the patches passed this test.

Figure 39: Rebar test on patches containing Flex Set, with the rebar placed over the area that failed the rebar test.

MG-Krete

The MG-Krete installed patches, like the FlexSet patches, appeared from visual inspection to be sound and intact. A few of the patches showed small surface pitting, but that was expected due to the release of the ammonia during the curing process of the patches, and because a retarder was not used on the patches at the time of installation. These cracks are likely not deep, and are not likely to be an issue moving forward.

The Patch with the large size and depth, which is conducted on the bridge deck, had the most of the small surface cracks, which was also expected due to of the patch volume. Figure 40 shows a patch of MG-Krete two and a half months after the winter installation, where multiple cracks can be seen on the surface of the patch. Figure 41 shows a crack on the patch of MG-Krete being measured at 1/32 inches (0.8 mm) wide. The entire patch passed the delamination test (scaling damage rating: 0).

Figure 40. MG-Krete Patch, showing cracking 2.5 months after installation

Figure 41. MG-Krete Patch, showing a crack that is approximately 1/32 inches (0.8 mm) wide, 2.5 months after installation.

One of the patches, from the time of the winter installation, had improper mixture. However, it seemed solid and showed no signs of failure. The west half of this patch, seen on the left of the patch pictured in Figure 42 shows that the improper proportioning is still visible, but there is no noticeable difference in durability between the two halves of the patch. The delamination test produced the same positive results for both halves of the patch, indicating it was well bonded.

Figure 42. MG-Krete patch with the improper mixture proportioning still visible.

Repcon 928

The Repcon 928 installed patches had one patch with a crack (scaling damage rating: 1). This crack was also small and expected, and was formed by a crack already present in the concrete pavement in which the patch was placed. The Repcon 928 patches also passed the delamination test, and showed no signs of concern for possible failure.

SR2000

The SR2000 installed patches did not have any visual cracks or deformities as of the July inspection. However, four of the patches did not pass the delamination test (scaling damage rating: 2). These patches, which were mostly installed on asphalt, gave off a hollow sound upon the delamination test during the July inspection. These four patches should be monitored closely over the course of this project, especially throughout the winter freeze-thaw cycles.

Product Comparisons

Based on the obtained results from the investigated repair materials, all the materials were simply ranked based on their performance, in which properties of each material is ranked from zero to 6 compared to the other materials. For example, in case of mass change, as can be seen in Table 17, Quikrete is ranked as 6 (worst; more than 8% mass loss), while Repcon 928 is ranked as 1 (best; no mass loss), indicating that Quikrete and Repcon exhibited the highest and the lowest mass change among the investigated materials. Pc, scaling damage, field performance, and price were other parameters that were taken into consideration. To rank the field performance of the materials scaling damage rating was applied. Besides, as compressive strength was not possible to be measure for all materials it was discarded for this regard. Table 17 summarizes the ranking of the investigated materials,

The overall ranking of the tested materials was then obtained by calculating the average of normalized responses, as presented in Table 17.

In general, mixture with lower sum of ranking is shown to ensure a greater mechanical and durability properties and are more desirable for future applications. The lowest and the highest sum of ranking were observed for MG-Krete and Delpatch, respectively.

Table 17. Ranking of evaluated repair materials

Material	Ranking					Sum of Rankings	Overall Ranking
	Mass Change	Pc	Scaling Damage	Field Performance	Price		
MG-Krete	2	1	1	1	3	8	1
Repcon	1	2	2	2	2	9	2
FlexSet	3	3	1	2	5	14	3
SR2000	3	5	1	3	4	16	5
Quikrete	5	4	3	2	1	15	4
Delpatch	4	6	1	2	5	18	6

CHAPTER VII

SUMMARY AND CONCLUSIONS

Summary

In this research, laboratory tests were conducted on a number of repair materials in an effort to compare their performance. For this purpose, an extensive literature review was performed on collecting information on patching repair materials. The review found little information on the acceptance criteria for partial-depth patching in cold climate regions. However, review of former research studies noted projects with a wide range of observations including both field and lab studies, which were used as references for selecting the materials in this project. From this information, eight repair materials were selected for testing, among which six of them were also used for field evaluations. Material types included one magnesium phosphate, four polymers, and three cementitious materials. After investigating the important properties of these materials, a testing program was developed to measure the basic mechanical and durability properties of the selected repair materials when subjected to F-T cycles. Tests for modulus of elasticity, UPV, weight loss, and scaling damage were performed after each 36 cycles and up to 300 cycles. Moreover, compressive strength and shrinkage of the materials were investigated.

To have a proper installation of the patches and to have the best chance to succeed for the products installed, there were a few factors regarding the patching process that should be noted. The issues are comprehensively discussed by Lesak (2014). Field surveys clearly indicated adequate performance for three of the selected materials including MG-Krete, Delpatch, and Repcon 982.

Potential Problems

This section documents the potential problems that were observed throughout the experimental program, which should be considered when choosing a product for future installations. All products used in this project had the potential for an early set. The polymeric materials (FlexSet, Delpatch and SR 2000) were sticky, which made mixing and finishing process of the products difficult when casting the materials in the molds. SR-2000 product does not have a specific guideline for mixture proportions, which make it difficult to come up with an adequate proportioning based on the ambient conditions including temperature. The SR-2000 and Delpatch products require the substrate to be primed prior to installation, which can delay the installation of the products up to an additional half an hour. The non-polymeric materials (MG-Krete, Quikrete, and RepCon 928) are easy materials to use. However, very rapid setting of MG-Krete makes it a little difficult to use.

Final Conclusions

Testing the hardened properties of the repair materials, exhibited very different stiffnesses for different repair materials. The polymeric materials showed high flexibility and therefore, ultimate compressive strengths could be only measured for the non-polymeric materials. Modulus of elasticity and shrinkage were tested to evaluate the compatibility of each material. Rigid materials like MG-Krete, Repcon 928, and Quikrete had the much higher values of elastic modulus than those of flexible materials (FlexSet, Delpatch, and SR2000). Shrinkage values were highly variable. However, except for FlexSet other materials met the requirement for 28-day shrinkage of less than 0.15%, which is set by ASTM 928. In addition, scaling damage visual inspection showed high scaling and debonding for Quikrete and Delpatch materials, respectively. In addition, based on the definition, slight to moderate scaling was observed for Repcon 928. The remained materials exhibited excellent conditions with no signs of scaling.

Prior to performing the partial-depth repair in the field, repair materials should be selected through the consideration and comparison of material acceptability and properties. The materials can be ranked based on material cost, field performance, and laboratory performance. The list of ranked materials is used to recommend adequate repair material. According to the results from performance ranking analysis, MG-Krete is shown to have the highest overall performance.

This research accomplished all of the objectives set out in this thesis, which consisted of:

- Determination of acceptable laboratory tests for comparative analysis of existing repair materials.
- Organize a guideline for a selection process of repair materials to be used for partial depth repair.
- Document the lab testing of selected repair materials for partial-depth repair.
- Compare and investigate the repair materials tested and their results based on the lab and field findings.

The laboratory and field testing that were performed for all of the products throughout this study were extensive and should provide enough data to analyze if any types of patch failure were to occur during the remainder of this project. Besides, based on the obtained results in this study, a final summary of the investigated materials is given below:

Final Summary of the Investigated Materials

MG-Krete

The MG-Krete installed patches appeared from visual inspection to be sound and intact. Testing MG-Krete in laboratory, no signs of scaling and degradation were observed. High compressive strength, high modulus of elasticity, high bonding, low shrinkage, excellent resistance to freezing and thawing cycles, and reasonable price of MG-Krete has made it an obvious choice for ODOT future repair applications.

Repcon 928

Regarding the field results, the Repcon 928 patches also passed the delamination test, and showed no signs of concern for possible failure. On the other hand, based on the obtained results in the laboratory, Repcon 928 exhibited excellent hardened specifications. However, this material had a scaling rating of 1 and 2 through the visual inspection in the field and the laboratory, respectively. Accordingly, its hardened properties and rational price has made it a reasonable alternative for MG-Krete, when expenses are a concern.

FlexSet

The FlexSet patches appeared sound and intact in both the field and the laboratory. The major reason that placed FlexSet as the third material in the list is high cost of this material.

Although, FlexSet showed the highest shrinkage value among the investigated materials, it was not an issue for the bonding of the corresponding specimens.

SR2000

The SR2000 installed patches did not have any visual cracks or deformities during the field inspections. However, some of the patches did not pass the delamination test and during the visual inspection, SR2000 received the highest scaling damage rating among the investigated materials. Besides, in according to the obtained results in the laboratory, after Delpatch, SR2000 received the lowest Pc value of 76%.

Quikrete

The Quikrete patches also passed the delamination test, and showed no signs that would suggest concern for possible failure in the field. However, Quikrete did not meet the requirements in the laboratories. It exhibited a significant mass loss after 120 F-T cycles and the repair material completely degraded.

Delpatch

The Delpatch installed patches also passed the visual evaluations and delamination test. Delpatch did not have any visual cracks or distress during the field inspections. In case of the laboratory, on the other hand, the Delpatch was the only material that debonded under F-T cycles. The first specimen made with the Delpatch debonded after 90 F-T cycles. However, the third specimen lasted for 300 F-T cycles.

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APPENDICES

Appendix A (Resonant Frequency)

Table 18. Raw results of resonant frequency test for (a) FlexSet, (b) MG-Krete, (c) Delpatch, (d) Quikrete, (e) Repcon 928, (f) SR2000, (g) Pavesaver, and (h) Pavemend SLQ.

(a)

M*	F-T*	Longitudinal			Avg.*	Transverse			Avg.
		1	2	3		1	2	3	
FlexSet	0	3021	1961	2756	2579	1431	1378	1378	1395
	30	2014	1795	1795	1868	1431	1378	1378	1395
	60	2173	2756	1908	2279	1431	1378	1378	1395
	90	3021	2279	2862	2720	1431	1378	1431	1413
	120	3074	2809	2809	2897	1431	1378	1378	1395
	150	3074	2766	2862	2900	1431	1378	1379	1396
	180	3021	3021	3021	3021	1431	1431	1431	1431
	210	3127	2968	3021	3038	1431	1431	1431	1431
	240	3175	2967	3021	3054	1456	1431	1457	1448
	270	3223	2966	3021	3070	1481	1431	1484	1465
	300	3074	2862	2809	2915	1431	1378	1487	1432

(b)

M	F-T	Longitudinal			Avg.	Transverse			Avg.
		1	2	3		1	2	3	
MG-Krete	0	4876	4929	4876	4893.667	2120	2173	2120	2137
	30	5038	5038	5035	5037	2226	2279	2226	2243
	60	5088	5088	5035	5070.333	2226	2332	2226	2261
	90	5088	5088	5035	5070.333	2226	2226	2226	2226
	120	5088	5191	5088	5122.333	2226	2279	2226	2243
	150	5088	5141	5088	5105.667	2226	2279	2226	2243
	180	5088	5141	5088	5105.667	2226	2279	2226	2243
	210	5114	5166	5114	5131.667	2226	2279	2226	2243
	240	5141	5191	5141	5157.667	2226	2279	2226	2243
	270	5114	5203	5114	5144	2226	2305	2252	2261
	300	5088	5215	5088	5130.333	2226	2332	2279	2279

(c)									
M	F-T	Longitudinal			Avg.	Transverse			Avg.
		1	2	3		1	2	3	
Delpatch	0	4611	4770	2279	3886	2014	2020	1855	1963
	30	1643	1802	1643	1696	2171	2172	2120	2154
	60	1643	2173	1696	1837	2171	1802	2120	2031
	90	2067	1060	Debonded	1563.5	2120	1060	Debonded	1590
	120	Debonded	954		954	Debonded	954		954
	150		1060		1060		901		901
	180		795		795		Debonded		-
	210		901		901				-
	240		1007		1007				-
	270		1007		1007				-
	300		1113		1113				-

(d)									
M	F-T	Longitudinal			Avg.	Transverse			Avg.
		1	2	3		1	2	3	
Quikrete	0	4505	4505	4505	4505	1961	1961	1961	1961
	30	4664	4664	4664	4664	2014	2014	2114	2047
	60	4664	4664	4664	4664	2067	2067	2067	2067
	90	4717	4664	4717	4699	2067	2014	2067	2049
	120	4823	4714	4770	4769	2067	2014	2067	2049
	150	4823	4717	4823	4787	2067	2014	2067	2049
	180	4849	4715	4823	4796	2067	2014	2040	2040
	210	4876	4714	4823	4804	2067	2014	2014	2031
	240	4876	4770	4823	4823	2067	2014	2014	2031
	270	4876	4714	4823	4804	2067	2014	2014	2031
	300	4876	4770	4823	4823	2067	2014	2014	2031

(e)									
M	F-T	Longitudinal			Avg.	Transverse			Avg.
		1	2	3		1	2	3	
Repcon 928	0	4823	4876	4823	4840	2120	2120	2067	2102
	30	4876	4876	4823	4858	2120	2120	2167	2135
	60	4929	4929	4876	4911	2173	2120	2173	2155
	90	4982	4982	4929	4964	2279	2173	2173	2208
	120	4982	5026	4982	4996	2226	2173	2173	2190
	150	5033	5088	5033	5051	2226	2226	2226	2226
	180	5060	5088	5060	5069	2226	2199	2226	2217
	210	5088	5088	5088	5088	2226	2173	2226	2208
	240	5088	5088	5088	5088	2226	2226	2173	2208
	270	5088	5088	5061	5079	2226	2173	2226	2208
	300	5088	5088	5035	5070	2226	2226	2173	2208

(f)									
M	F-T	Longitudinal			Avg.	Transverse			Avg.
		1	2	3		1	2	3	
SR2000	0	3339	3399	3551	3429	1590	1537	1643	1590
	30	2915	2865	3127	2922	1431	1484	1537	1484
	60	2882	2849	3121	2950	1486	1590	1537	1538
	90	2872	2840	3097.5	2936	1485	1563.5	1537	1524
	120	2862	2832	3074	2922	1484	1537	1537	1510
	150	2756	2832	3127	2905	1484	1537	1537	1510
	180	2756	2815	3127	2899	1454	1537	1537	1509
	210	2746	2813	3026	2861	1454	1537	1537	1509
	240	2706	2815	2926	2815	1454	1537	1537	1509
	270	2706	2792	2872	2790	1454	1537	1537	1509
	300	2676	2777	2872	2775	1454	1537	1537	1509

(g)									
M	F-T	Longitudinal			Avg.	Transvers			Avg.
		1	2	3		1	2	3	
Pavesaver	0	4293	4346	4187	4275	1854	1908	1802	1855
	30	4399	4452	4293	4381	1908	1961	1855	1908
	60	4399	4452	4293	4381	1855	1911	1855	1874
	90	4399	4452	4346	4399	1854	1908	1906	1889
	120	4346	4399	4293	4346	1908	1908	1908	1908
	150	4346	4452	4246	4348	1855	1908	1855	1873
	180	4346	4399	4246	4330	1855	1908	1855	1873
	210	4346	4399	4246	4330	1855	1908	1855	1873
	240	4346	4399	4246	4330	1855	1908	1855	1873
	270	4346	4399	4240	4328	1855	1908	1855	1873
	300	4346	4329	4246	4307	1855	1908	1855	1873

(h)									
M	F-T	Longitudinal			Avg.	Transvers			Avg.
		1	2	3		1	2	3	
Pavemend SLQ	0	4187	4240	4134	4187	1802	1855	1855	1837
	30	4240	4346	4240	4014	1908	1908	1855	1890
	60	4240	4346	4239	4275	1908	1908	1855	1908
	90	4293	4346	4246	4295	1908	1908	1855	1908
	120	4346	3498	4199	4014	1908	1911	1908	1909
	150	4346	Debonded	4199	4273	1908	Debonded	1908	1908
	180	4346		4139	4243	1908		1908	1908
	210	4346		4134	4240	1908		1908	1908
	240	4346		4134	4240	1908		1908	1908
	270	4346		4134	4240	1908		1908	1908
	300	4346		4134	4240	1908		1908	1908

* M: Material, F-T: Freeze-thaw cycle, Avg: Average

Appendix B (UPV)

Table 19. Raw results of ultrasonic pulse velocity test for (a) FlexSet, (b) MG-Krete, (c) Delpatch, (d) Quikrete, (e) Repcon 928, (f) SR2000, (g) Pavesaver, and (h) Pavemend SLQ

(a)

M*	F-T*	UPV (ft/sec)			Avg.*
		1	2	3	
FlexSet	0	5425	5020	4748	5064
	30	5817	5828	6094	5913
	60	5916	6895	6610	6473
	90	6266	6510	6349	6375
	120	7656	6988	6562	7068
	150	6366	6628	6663	6552
	180	6514	6786	6485	6595
	210	6218	6960	6714	6630
	240	6627	7010	7015	6884
	270	6541	6874	6926	6780
	300	6845	6720	7168	6911

(b)

M	F-T	UPV (ft/sec)			Avg.
		1	2	3	
MG-Krete	0	13021	12870	13495	13128
	30	13346	13123	13387	13285
	60	12672	11455	11494	11873
	90	11655	12531	12165	12117
	120	11517	12330	12286	12117
	150	11660	12318	12560	12179
	180	11717	12336	12840	12297
	210	11720	12284	13175	12393
	240	11694	12251	12779	12241
	270	11698	11456	13147	12100
	300	11706	11223	13072	12000

(c)

M	F-T	UPV (ft/sec)			Avg.
		1	2	3	
Delpatch	0	1676	1682	1690	1682
	30	1473	1529	1587	1529
	60	1412	1507	1504	1474
	90	1312	1425	Debonded	1368
	120	Debonded	1175		1175
	150		1025		1025
	180		Debonded		-
	210				-
	240				-
	270				-
	300				-

(d)

M	F-T	UPV (ft/sec)			Avg.
		1	2	3	
Quikrete	0	12920	13947	14006	13624
	30	12194	12674	13889	12919
	60	11862	12210	13074	12382
	90	12920	12531	12771	12740
	120	12874	12471	11718	12740
	150	11725	11065	11193	11327
	180	Debonded	Debonded	Debonded	-
	210				-
	240				-
	270				-
	300				-

(e)					
M	F-T	UPV (ft/sec)			Avg.
		1	2	3	
Repcon 928	0	14202	13634	13220	13685
	30	13441	13550	13620	13537
	60	10804	12050	11417	11423
	90	10225	11338	10870	10811
	120	9804	10288	11655	10582
	150	10804	9950	10417	10390
	180	10225	10338	10870	10477
	210	10004	11128	10989	10707
	240	10790	11562	10419	10923
	270	10512	10879	9015	10135
	300	9015	10181	9749	9648

(f)					
M	F-T	UPV (ft/sec)			Avg.
		1	2	3	
SR2000	0	4735	4617	4916	4756
	30	2884	2782	3022	2896
	60	2718	2714	2952	2795
	90	2372	2533	2514	2473
	120	2189	2374	2379	2314
	150	2070	2212	2103	2128
	180	2070	2212	2011	2098
	210	2100	2170	1989	2086
	240	2065	2089	1985	2046
	270	2017	1970	1914	1967
	300	2019	1958	1914	1964

(g)					
M	F-T	UPV (ft/sec)			Avg.
		1	2	3	
Pavesaver	0	9662	8818	10650	9710
	30	9891	10132	10289	10104
	60	9430	9371	9952	9584
	90	9093	8834	9573	9166
	120	8814	8155	9252	8740
	150	8393	7734	9039	8388
	180	8380	7521	8860	8253
	210	8301	7342	8739	8127
	240	8180	7121	8653	7984
	270	8161	7074	8616	7950
	300	8255	7017	8694	7988

(h)					
M	F-T	UPV (ft/sec)			Avg.
		1	2	3	
Pavemend SLQ	0	12870	9259	12038	11389
	30	10256	10449	11753	10819
	60	10206	10346	11650	10734
	90	10162	10272	11557	10664
	120	10127	10237	11492	10619
	150	10088	Debonded	11441	10765
	180	10060		11397	10729
	210	10024		11350	10687
	240	10007		11299	10653
	270	10010		11261	10636
	300	10012		11254	10633

* M: Material, F-T: Freeze-thaw cycle, Avg: Average

Appendix C (Mass Change)

Table 20. Raw results of mass change evaluation for (a) FlexSet, (b) MG-Krete, (c) Delpatch, (d) Quikrete, (e) Repcon 928, (f) SR2000, (g) Pavesaver, (h) Pavemend SLQ

(a)						
M*	F-T*	Weight (lb)			Avg.*	Mass Reduction
		1	2	3		
FlexSet	0	14.2	14.8	14.5	14.50	
	30	14.3	14.8	14.5	14.53	-0.23
	60	14.1	14.8	14.5	14.47	0.23
	90	14.1	14.8	14.4	14.43	0.46
	120	14.1	14.8	14.4	14.43	0.46
	150	14.2	14.7	14.3	14.40	0.69
	180	14.2	14.7	14.3	14.37	0.92
	210	14.2	14.7	14.3	14.40	0.69
	240	14.2	14.7	14.3	14.40	0.69
	270	14.1	14.7	14.3	14.37	0.92
	300	14.1	14.7	14.3	14.37	0.92

(b)						
M	F-T	Weight (lb)			Avg.	Mass Reduction
		1	2	3		
MG-Krete	0	14.8	14.8	15.0	14.87	
	30	14.8	14.8	15.0	14.87	0.05
	60	14.8	14.8	15.0	14.87	0.05
	90	14.8	14.8	15.0	14.87	0.05
	120	14.9	15.0	15.0	14.87	0.05
	150	14.8	14.8	15.0	14.87	0.05
	180	14.8	14.8	15.0	14.87	0.05
	210	14.8	14.8	15.0	14.87	0.05
	240	14.8	14.8	15.0	14.87	0.05
	270	14.8	14.8	14.9	14.83	0.22
	300	14.8	14.8	15.0	14.87	0.05

(c)						
M	F-T	Weight (lb)			Avg.	Mass Reduction
		1	2	3		
Delpatch	0	13.7	13.6	13.6	13.63	
	30	13.9	13.9	13.8	13.87	-1.71
	60	13.6	13.5	13.5	13.53	0.73
	90	13.5	13.5	Debonded	13.50	0.98
	120	Debonded	13.4		13.40	1.71
	150		13.5		13.50	0.98
	180		13.4		13.40	1.71
	210		13.4		13.40	1.71
	240		13.3		13.30	2.44
	270		13.3		13.30	2.44
	300		13.3		13.30	2.44

(d)						
M	F-T	Weight (lb)			Avg.	Mass Reduction
		1	2	3		
Quikrete	0	15.2	15.3	15.3	15.27	
	30	15.2	15.3	15.4	15.30	-0.22
	60	15.2	15.2	15.2	15.20	0.44
	90	15.2	15.2	15.2	15.20	0.44
	120	14.7	15.0	14.8	14.83	2.84
	150	14.6	14.9	14.8	14.77	3.28
	180	14.6	14.9	14.8	14.77	3.28
	210	14.3	14.7	14.3	14.43	5.46
	240	14.1	14.6	14.2	14.30	6.33
	270	14.0	14.3	14.0	14.10	7.64
	300	13.9	14.1	13.9	13.97	8.52

(e)						
M	F-T	Weight (lb)			Avg.	Mass Reduction
		1	2	3		
Repcon 928	0	15.0	15.0	15.0	15.00	
	30	15.1	15.1	15.0	15.07	-0.44
	60	15.0	15.0	15.0	15.00	0.00
	90	15.0	15.0	15.0	15.00	0.00
	120	15.0	15.1	15.0	15.03	-0.22
	150	15.1	15.2	15.0	15.10	-0.67
	180	15.1	15.2	15.0	15.10	-0.67
	210	15.1	15.2	15.0	15.10	-0.67
	240	15.1	15.2	15.0	15.10	-0.67
	270	15.1	15.2	15.0	15.10	-0.67
	300	15.1	15.2	15.0	15.10	-0.67

(f)						
M	F-T	Weight (lb)			Avg.	Mass Reduction
		1	2	3		
SR2000	0	14.1	14.2	14.2	14.17	
	30	14.0	14.1	14.2	14.10	0.47
	60	14.0	14.0	14.2	14.07	0.71
	90	14.0	14.0	14.3	14.10	0.47
	120	13.8	14.0	14.2	14.00	1.18
	150	13.8	14.0	14.2	14.00	1.18
	180	13.8	14.0	14.2	14.00	1.18
	210	13.8	14.0	14.2	14.00	1.18
	240	13.8	14.0	14.2	14.00	1.18
	270	13.8	14.0	14.2	14.00	1.18
	300	13.8	14.0	14.2	14.00	1.18

(g)						
M	F-T	Weight (lb)			Avg.	Mass Reduction
		1.0	2.0	3.0		
Pavesaver	0	15.0	14.6	14.4	14.67	
	30	14.9	14.7	14.5	14.70	-0.23
	60	14.9	14.7	14.5	14.70	-0.23
	90	15.0	14.7	14.5	14.73	-0.45
	120	15.0	14.7	14.5	14.73	-0.45
	150	15.0	14.7	14.5	14.73	-0.45
	180	15.0	14.7	14.5	14.73	-0.45
	210	15.0	14.7	14.5	14.73	-0.45
	240	15.0	14.7	14.5	14.73	-0.45
	270	15.0	14.7	14.5	14.73	-0.45
	300	15.0	14.7	14.5	14.73	-0.45

(h)						
M	F-T	Weight (lb)			Avg.	Mass Reduction
		1.0	2.0	3.0		
Pavemend SLQ	0	14.6	14.7	15.0	14.77	
	30	14.4	14.8	15.2	14.80	-0.23
	60	14.5	14.8	15.2	14.83	-0.45
	90	14.6	14.9	15.3	14.93	-1.13
	120	14.6	14.8	15.2	14.87	-0.68
	150	14.6	Debonded	15.2	14.90	-0.90
	180	14.6		15.2	14.90	-0.90
	210	14.6		15.2	14.90	-0.90
	240	14.6		15.2	14.90	-0.90
	270	14.6		15.2	14.90	-0.90
	300	14.6		15.2	14.90	-0.90

* M: Material, F-T: Freeze-thaw cycle, Avg: Average

Appendix D (Pull-Off)

Table 21. Raw results of pull-off test for (a) FlexSet, (b) MG-Krete, (c) Delpatch, (d) Quikrete, (e) Repcon 928, (f) SR2000, (g) Pavesaver, and (h) Pavemend SLQ.

(a)		
	FlexSet	
#	Bond Strength (lbf)	Failure mode
1	500	C
2	475	C
3	550	C
4	350	C
5	425	C
6	400	C

(b)		
	MG-Krete	
#	Bond Strength (lbf)	Failure mode
1	3225	D
2	3300	D
3	2800	B
4	2700	B
5	2500	B
6	2450	B

(c)		
	Delpatch	
#	Bond Strength (lbf)	Failure mode
1	0	-
2	0	-
3	0	-
4	0	-
5	0	-
6	0	-

(d)		
	Quikrete	
#	Bond Strength (lbf)	Failure mode
1	1425	C
2	1900	C
3	Deteriorated. No room for coring	
4		
5		
6		

(e)		
	SR2000	
#	Bond Strength (lbf)	Failure mode
1	575	C
2	200	B
3	325	B
4	100	B
5	225	B
6	250	B

(f)		
	Repcon 928	
#	Bond Strength (lbf)	Failure mode
1	2500	B
2	3000	C
3	3000	C
4	2325	C
5	2800	C
6	2500	C

(g)		
#	Pavesaver	
	Bond Strength (lbf)	Failure mode
1	1200	C
2	1000	C
3	1300	C
4	1250	C
5	0	A
6	0	A

(h)		
#	Pavemend SLQ	
	Bond Strength (lbf)	Failure mode
1	400	C
2	375	C
3	Debonded after 150 F-T	
4		
5	Debonded during coring	
6		

Appendix E (Shrinkage)

Table 22. Raw results of length change measurment for (a) FlexSet, (b) MG-Krete, (c) Delpatch, (d) Quikrete, (e) Repcon 928, (f) SR2000, (g) Pavesaver, and (h) Pavemend SLQ.

(a)				
M*	Age	Length (in)		Avg.*
		1	2	
FlexSet	1	0.1154	0.1052	0.1103
	2	0.1014	0.0998	0.1006
	3	0.0957	0.0926	0.09415
	5	0.0906	0.0956	0.0931
	7	0.0846	0.0886	0.0866
	9	0.0816	0.0826	0.0821
	14	0.0756	0.0777	0.07665
	21	0.0726	0.0666	0.0696
	28	0.0625	0.0664	0.06445
	44	0.0624	0.0662	0.0643
	56	0.0598	0.0636	0.0617
	60	0.0598	0.0636	0.0617
	75	0.0598	0.0636	0.0617
	90	0.0598	0.0636	0.0617
	105	0.0598	0.0636	0.0617

(b)				
M	Age	Length (in)		Avg.
		1	2	
MG-Krete	1	0.0617	0.0547	0.0582
	2	0.0616	0.0546	0.0581
	3	0.0616	0.0546	0.0581
	5	0.0615	0.0546	0.05805
	7	0.0615	0.0546	0.05805
	9	0.0614	0.0546	0.058
	14	0.0613	0.0546	0.05795
	21	0.0611	0.0546	0.05785
	28	0.0611	0.0546	0.05785
	44	0.0611	0.0546	0.05785
	56	0.0611	0.0546	0.05785
	60	0.0611	0.0546	0.05785
	75	0.0611	0.0546	0.05785
	90	0.0611	0.0546	0.05785
	105	0.0611	0.0546	0.05785

(c)				
M	Age	Length (in)		Avg.
		1	2	
Delpatch	1	0.0624	0.0626	0.0625
	2	0.0622	0.063	0.0626
	3	0.0621	0.0623	0.0622
	5	0.062	0.0622	0.0621
	7	0.062	0.0621	0.06205
	9	0.0619	0.0621	0.062
	14	0.0618	0.0621	0.06195
	21	0.0618	0.0621	0.06195
	28	0.0618	0.0621	0.06195
	44	0.0618	0.0621	0.06195
	56	0.0618	0.0621	0.06195
	60	0.0618	0.0621	0.06195
	75	0.0618	0.0621	0.06195
	90	0.0618	0.0621	0.06195
	105	0.0618	0.0621	0.06195

(d)				
M	Age	Length (in)		Avg.
		1	2	
Quikrete	1	0.0625	0.0627	0.0626
	2	0.0619	0.062	0.06195
	3	0.0614	0.0618	0.0616
	5	0.0614	0.0615	0.06145
	7	0.0614	0.0613	0.06135
	9	0.0614	0.0614	0.0614
	14	0.0614	0.06086	0.06113
	21	0.0612	0.0608	0.061
	28	0.06026	0.0608	0.06053
	44	0.06026	0.0608	0.06053
	56	0.0603	0.061	0.06065
	60	0.0603	0.061	0.06065
	75	0.06026	0.0608	0.06053
	90	0.0625	0.0627	0.0626
	105	0.0619	0.062	0.06195

(e)				
M	Age	Length (in)		Avg.
		1	2	
Repcon 928	1	0.062	0.0625	0.06245
	2	0.062	0.0623	0.06215
	3	0.0619	0.0621	0.062
	5	0.0619	0.062	0.06195
	7	0.0618	0.0618	0.0618
	9	0.0618	0.0619	0.06185
	14	0.0617	0.0619	0.0618
	21	0.0615	0.0617	0.0616
	28	0.0613	0.0615	0.0614
	44	0.0612	0.0614	0.0613
	56	0.0612	0.0614	0.0613
	60	0.0612	0.0614	0.0613
	75	0.0612	0.0614	0.0613
	90	0.0611	0.0614	0.06125
	105	0.0612	0.0614	0.061305

(f)				
M	Age	Length (in)		Avg.
		1	2	
SR2000	1	0.0617	0.0615	0.0616
	2	0.0615	0.0614	0.06145
	3	0.061	0.0609	0.06095
	5	0.0606	0.0605	0.06055
	7	0.0604	0.0604	0.0604
	9	0.06	0.0601	0.06005
	14	0.0598	0.0598	0.0598
	21	0.0598	0.0598	0.0598
	28	0.0589	0.0597	0.0593
	44	0.0589	0.0597	0.0593
	56	0.0589	0.0597	0.0593
	60	0.0589	0.0597	0.0593
	75	0.0589	0.0597	0.0593
	90	0.0589	0.0597	0.0593
	105	0.0589	0.0597	0.0593

(g)				
M	Age	Length (in)		Avg.
		1	2	
Pavesaver	1	0.0612	0.0616	0.0614
	2	0.0613	0.0614	0.06135
	3	0.0613	0.0613	0.0613
	5	0.0612	0.0613	0.06125
	7	0.0608	0.061	0.0609
	9	0.0607	0.0609	0.0608
	14	0.0605	0.0607	0.0606
	21	0.0606	0.0608	0.0607
	28	0.0606	0.0607	0.06065
	44	0.0604	0.0606	0.0605
	56	0.0606	0.0606	0.0606
	60	0.0607	0.0607	0.0607
	75	0.0605	0.0607	0.0606
	90	0.0606	0.0609	0.06075
	105	0.0606	0.0607	0.06065

(h)				
M	Age	Length (in)		Avg.
		1	2	
Pavemend SLQ	1	0.0617	0.062	0.06185
	2	0.0614	0.0618	0.0616
	3	0.0614	0.0617	0.06155
	5	0.0612	0.0615	0.06135
	7	0.0608	0.0612	0.061
	9	0.0603	0.0606	0.06045
	14	0.0598	0.0601	0.05995
	21	0.0597	0.0604	0.06005
	28	0.0597	0.0601	0.0599
	44	0.0597	0.0599	0.0598
	56	0.0597	0.0601	0.0599
	60	0.0597	0.06	0.05985
	75	0.0597	0.0601	0.0599
	90	0.0597	0.0601	0.0599
	105	0.0597	0.06	0.05985

* M: Material, Avg: Average

Appendix F (Compressive Strength)

Table 23. Raw results of length change measurment for (a) FlexSet, (b) MG-Krete, (c) Delpatch, (d) Quikrete, (e) SR2000, (f) Repcon 928, (g) Pavesaver, (h) Pavemend SLQ, (i) Base material

(a)

M*	Age	Compressive strength (psi)			Avg.*
		1	2	3	
FlexSet	3 hr	NA	NA	NA	-
	1 day	NA	NA	NA	-
	7 days	NA	NA	NA	-

(b)

M	Age	Compressive strength (psi)			Avg.
		1	2	3	
MG-Krete	3 hr	3047	3048	3057	3050
	1 day	4788	4808	4795	4797
	7 days	5560	5580	5603	5581

(c)

M	Age	Compressive strength (psi)			Avg.
		1	2	3	
Delpatch	3 hr	NA	NA	NA	-
	1 day	NA	NA	NA	-
	7 days	NA	NA	NA	-

(d)

M	Age	Compressive strength (psi)			Avg.
		1	2	3	
Quikrete	3 hr	3117	3102	3110	3109
	1 day	4594	4615	4607	4605
	7 days	5993	6039	6013	6015

(e)

M	Age	Compressive strength (psi)			Avg.
		1	2	3	
SR2000	3 hr	NA	NA	NA	-
	1 day	NA	NA	NA	-
	7 day	NA	NA	NA	-

(f)

M	Age	Compressive strength (psi)			Avg.
		1	2	3	
Repcon 928	3 hr	2256	2236	2258	2246
	1 day	5135	5064	5104	5101
	7 day	6349	6368	6252	6323

(g)					
M	Age	Compressive strength (psi)			Avg.
		1	2	3	
PaveSaver	3 hr	NA	NA	NA	-
	1 day	NA	NA	NA	-
	7 days	NA	NA	NA	-

(h)					
M	Age	Compressive strength (psi)			Avg.
		1	2	3	
Pavemend SLQ	3 hr	2614	2683	2683	2660
	1 day	4745	4666	4701	4704
	7 days	5339	5468	5358	5388

(i)					
M	Age	Compressive strength (psi)			Avg.
		1	2	3	
Base Material	7 days	3732	3725	3731	3729
	28 days	4617	4631	4613	4620

* M: Material, Avg: average