Enhanced Performance Criteria for Acceptance of Rigid Pavement Patching Materials Used in Cold Climate Regions

A Thesis

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Dedication

This thesis is dedicated to my late father Archie E. Dailey. I had the pleasure of working with my dad virtually every day for more than twenty years. He involved me with the family business at a very early age where I learned many important keys to success in life. During that time he bestowed upon me a work ethic that made returning to college and completing engineering school a possibility. Thank You DAD.

Abstract

The primary goal for this study was to develop an enhanced testing regimen for the approval of rapid set cementitious products to be used as patching materials in rigid pavements. A twofold testing procedure was used in conducting the research on the selected materials. The beginning phase of the project focused on the standard acceptance criteria used by most departments of transportation. An additional set of tests were conducted to formulate a plan for future testing procedures and acceptance criteria for patch materials to be used in colder climates.

The research conducted for this study provided insight as to which tests should be conducted during the acceptance process for rapid set cementitious materials. The current criterion (ASTM C928) for accepting these materials was found to be inadequate, especially for use in colder climate regions. Data analysis discovered various correlations between some of the tests that were performed. These findings allowed certain tests to be removed from the testing regimen. The tests that are recommended to be implemented for the acceptance of patching materials in colder climates include: compressive strength test at 3 hours and 28 days, shrinkage testing, freeze-thaw testing with reports on mass loss and initial dynamic modulus, setting times, modulus of elasticity and consistency/workability of concrete. The study also indicated that certain tests may be unnecessary, these include: flexural strength, coefficient of thermal expansion, and abrasion resistance. More research is necessary to expand the data set and reinforce the findings from this study.

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Chapter 1: Introduction of the project

Introduction to Partial Depth Patching

Over the course of their service life, concrete pavements undergo significant traffic and climatic loadings leading to a gradual accumulation of damage. This accumulation of damage and distresses comes from effects of changing weather conditions (temperature and moisture) and the continuous vehicular traffic. Repeated environmental and traffic loading leads to cracking and spalling of the concrete at the joint edges. This pavement distress can also be created from stresses in the concrete due to incompressible material accumulating in the joint. This leads to the slab not being able to expand and contract properly. Deficient aggregates also will cause spalling. If an aggregate has a high coefficient of thermal expansion and contraction, this can weaken the areas around joints and cracks during fluctuating temperatures (Chen et al., 2009). Spalls can be cracks, chips and breaks that occur at slab edges along the joints or cracks. A typical spalled joint in concrete pavement can be viewed in Figure 1. Spalling leads to a reduced serviceability for the concrete roadway and can potentially cause safety concerns for the travelers. All of these areas of distresses need to be patched prior to the point when their severity impedes safe and smooth traffic operations on the roadway.

The depth of the damage can be anywhere from slight surface damage to cracks extending to the bottom of the slab. When this damage is contained in the upper ½ of the slab thickness, partial depth repair (PDR) is the preferred method (Symons, 1999). If the spall penetrates to a depth below ½ of the slab thickness a full depth repair is usually recommended (Johnson, 2012). Many state's Department of Transportations (DOT's) utilize PDR as routine practice to maintain the concrete pavements, for example, Minnesota, Iowa, California, Colorado, Kansas, Missouri and Wisconsin DOTs use this method. The process of partial depth repair actually started in Minnesota in the early 1980's. (International Grooving and Grinding Association, 2011) As one of the first projects, the portions of Trunk Highway 61 near Hastings and Duluth were repaired using the PDR method. The initial trials were conducted using the sawing and chipping to prepare the patches. The early projects were not met with a high level of success; this led to MnDOT proposing the use of a grinder for material removal (similar to one shown in Figure 2) which led to much higher rates of success (International Grooving and Grinding Association, 2011).

Figure 1: A spall ready for grinding

Figure 2: The grinding machine removing material on a spalled section of pavement

Problem Description

Unique Cold Climate Issues

The patches that are installed in colder climates undergo a much harsher set of climatic changes than patches placed in warmer climates. These climatic conditions lead to a greater fluctuation in the stresses realized not only by the pavement but also by the patches themselves.

The first aspect of this is the temperature changes that are realized throughout the year. Temperature swings from the summer months to the winter months is an important factor to consider. For instance a pavement slab in Florida will typically experience a 70°F temperature difference from the average summer time temperature to the average winter time temperature. Whereas, a slab located in Minnesota will see a 120°F difference. This is significant when considering thermally induced expansion and contraction of the materials. For the same material the thermal deformation depends only on the temperature differences. This indicates that the slab in Minnesota will expand and contract nearly twice as much as the slab in Florida throughout the year. This causes a greater opening of the joints between the slabs, when the slab contracts during cooler weather. This allows for fines to collect in the joint, potentially leading to the locking of the joint. The inactive joint causes an excessive stress build up at the joint causing spalling. In the case of patches, this becomes a greater concern when there is a patch present at the edge of the transverse joints of the slab.

Another consideration is related to the daily temperature effects on the slabs. The individual slabs in jointed concrete pavement curl upwards at the edges because of the difference between day and night time temperatures (Swanlund and Tyson, 2010). The patch material must bend and flex in a similar manner as the PCC of the pavement slab to stay bonded.

Important Aspects of Patch Failure

The bond between a patch material and the existing pavement slab is of paramount importance. An un-bonded patch is free to move about and eventually will be ejected out of the patch area. Herein bond is defined as the mechanism (chemical or mechanical) that allows load transfer from one side of an interface to another. Once that is broken there is no longer load transfer from one material to the other which would then be considered a patch failure.

Resistance to deicing chemicals is another property of importance for materials used in colder climates. The integrity of a patch in the field can rapidly degrade if the material is susceptible to surface erosion when exposed to deicing compounds.

Material stiffness can also have an effect on the overall performance of a completed patch. The existing pavement slabs flex due to temperature and traffic loading, if the patch material's stiffness is too great it will lead to a concentration of stress in the patch material, and at the bond interface. The concentration of this stress can contribute to the bond interface being compromised.

Freeze thaw durability of the material is of concern as well. Pavements in colder climates undergo a series of freezing and thawing cycles each year. The materials used to patch these pavements must be able to withstand the potential damage that can be associated with these cycles.

The rate at which a patching material gains strength is important to determine how long a lane must remain closed. Rapid set materials are used for the purpose of shortening lane closure times. If there is insufficient strength present when traffic resumes the patch can be compromised.

Need for this Study

There is a readily apparent need for enhanced acceptance criteria for rapidly setting cementitious patching material for use in partial depth repair. The material must rapidly gain strength to allow the roadway to be reopened to traffic quickly. In addition, the patch should bond well to the substrate to prevent the patch from separating from the existing material, and be durable enough to withstand the harsh Minnesota winters. MnDOT in previous reports has indicated that patch failures are higher than anticipated. The annual roadway condition report for 2011 indicated that on an average basis that patches have been failing within one year. The report for that year presented evidence that there were 232 miles of patched roadways which had performed below expectations (MnDOT, 2012).

The impact of the proposed research will be better performance criteria that can be used to compare the materials tested in this program to new materials that will certainly be developed in the future.

Objective of this Study

Considering the unique challenges presented to patching materials in colder climates a new system of acceptance criteria is desirable. The current acceptance standards are general and do not require climatic considerations, although some are recommended. The goal is to develop a more appropriate set of tests and performance criteria so that the materials that are chosen for partial depth repair will perform better and last longer once in the field. This will be achieved by extending the current standards to include tests that represent colder climate conditions and eliminating those that may not provide additional information about the performance of patches. Furthermore, through the testing efforts of this study a comprehensive evaluation of various patching products that are currently approved for use in Minnesota will be achieved.

Research Approach

The primary approach undertaken in this study was to focus on laboratory tests. The ASTM C928 specification for rapid setting cementitious materials was employed as well as tests that were developed by the researchers. The intention of this research is to develop laboratory procedures that can indicate which materials are viable for use in the field. The following is a compressed step by step procedure that was used.

- Test 13 rapid set cementitious products and mixes using the current acceptance criteria as a guide, ASTM C928 specification;
- Analyze the data that is collected to find points of interest and compare patch material properties with typical paving concrete; and,
- Choose 4 products from the original list to continue on to a more rigorous set of tests later in the project
    - The tests in this phase are more tailored to climatic effects on the materials.

Results from both phases are compiled and analyzed to determine if these tests are viable and necessary for acceptance of patching materials.

Scope of the Current Study

Repair types

The study being performed deals directly with the materials involved in partial depth repairs (PDR). MnDOT has three different classifications of partial depth repairs. These are Type BA, Type BE and Type B3 (Masten, 2011). A comparison of the three types is presented in Table 1. Schematics of the common partial depth repairs are located in the Appendix-A.

Table 1: Partial depth repair types

Type	Definitions
BA	Repair is contained above the level of the dowel bars Patch width is minimum of 10" wide Patch is a maximum of 6' long
BE	Repair depth is below dowel bars (full depth) Tie bar steel reinforcement must be provided in patch Reinforcement must extend a minimum of 4" into sound concrete and be exposed a minimum of 4" into the patch material
B3	Same as type BA except the patch length is longer than 6'

Even though the Type BE repair extends to the full depth of the pavement it is not considered a full depth repair by MnDOT. Full depth repair as defined by MnDOT includes the replacement of load transferring devices, dowel bars.

The type of damage that coincides with partial depth repair is for the most part functional; the roadway's purpose is diminished but is still structurally sound. In some cases mild structural damage can be present and still be considered for partial depth repair. When there is extensive structural damage present the two options that are considered include; full depth repair or complete reconstruction. Full depth repair involves removing either an entire slab or a large portion of a slab down to the subgrade below.

Materials

A total of thirteen mix designs were chosen to be used in this study. They have been chosen in coordination with a technical advisory panel composed of MnDOT engineers and industry professionals. They are all rapid set cementitious materials. Table 2 contains the list of materials to be used.

Table 2: Mixes to be used in this study

Material, Source/Manufacturer
3U18, MnDOT Mix TCC
3U18M, MnDOT Mix TCC
3U18, MnDOT District 3 Mix 1
3U18, MnDOT District 3 Mix 2
Futura 15, W.R. Meadows
Futura 45, W.R. Meadows
FiveStar Highway Patch, Five Star Products
Mono Patch, BINDAN Corp.
Akona, TCC Gypsum based
Rapid Set Concrete Mix, CTS Cement Manufacturing Corp.
Pavemend SLQ, Cera Tech Inc.
Pavemend SL, Cera Tech Inc.
Rapid Patch Taconite Mix, TCC

Organization of Thesis

This thesis begins by researching previous work performed on the subject matter. An extensive review of literature was performed to gain insight on where to begin and to identify areas of interest (Chapter 2). Following the literature review is a compilation of the tests to be employed during the research for this study. This section also contains all of the data analysis performed during the initial testing phase of the project (Chapter 3). The next section is devoted to the enhanced testing of the final four materials. The tests in this section were chosen to measure properties that are of significant importance when considering cold climate regions (Chapter 4). The final research portion of this study presents the methods used during partial depth patching. Current methods of patch preparation through patching material placement were evaluated. Recommendations for the most proven cold climate patching practices are located within (Chapter 5). The end of this thesis is dedicated to analyzing all of the data as a whole and making the appropriate conclusions and recommendations for the entire study (Chapter 6).

Chapter 2: Literature Review

Introduction and Review of State DOT Practices

Minnesota Department of Transportation (MnDOT) currently has 34 approved bag mixes of rapid set cementitious materials used for concrete pavement repair (CPR) (MnDOT, 2012). These products have passed the minimum requirements set forth by MnDOT. The approval process is directly based on the ASTM C928 specifications. The ASTM C928 has certain requirements on minimum compressive strength, bond strength, aversion to length change, consistency and scaling resistance.

Table 3 &Table 4 show the tests and the required properties. There are three different types of concrete or mortar that are listed in the ASTM C928; R1, R2 and R3. The different types of mortars are rated based on strength gain over time. For this study all of the materials must adhere to the R3 mortar type which is most conducive to partial depth patching.

While some of the most important material properties are recommended, they are not required. These include; set time, coefficient of thermal expansion and freeze-thaw resistance. MnDOT standard construction specifications reference the pre-bagged patch mix grade 3U18. This mix is only specified for mix proportions and aggregate gradation. Other Departments of Transportation (DOT's) also rely on the ASTM C928 specification for purposes of rapid set material acceptance. In South Dakota another requirement for patching materials is that the concrete mix design must reach 4,000 psi within 6 hours.

Table 3: Tests and property requirements of the ASTM C928 specification for the acceptance of patching mixes (Time dependent)

Property	Test Specification	3 hour	1 day	7 days	28 days
Compressive strength min. (psi)	ASTM C39/C109				
R1 concrete/mortar		500	2000	4000	
R2 concrete/mortar		1000	3000	4000	
R3 concrete/mortar		3000	5000	5000	
Bond strength min. (psi)	ASTM C882				
R1, R2, R3 concrete/mortar			1000	1500	
Length change based on	ASTM C157				
3 hour length (% change)					
Max increase in water @28 days					0.15
Max decrease in air @28 days					-0.15

Table 4: Tests and property requirements of ASTM C 928 specification for acceptance of patching mixes (Time independent)

Property	Test Specification			
Consistency of concrete/mortar	ASTM C143	R1 consistency 15 minutes after mixing liquid is added	R2 and R3 consistency 5 minutes after mixing liquid is added	R1, R2 and R3
Slump of concrete (in)		3	3	
Flow of mortar (%)		100	100	
Scaling resistance to deicing chemicals after 25 cycles of freezing and thawing	ASTM C672			
Concrete, max visual rating				2.5
Mortar, max scaled material, lb/ft^2				1

Ziegler and Levi recommended that all spall repairs must be conducted when the air temperature is above 40 °F (2008). The North Dakota DOT specifies a maximum water content and minimum placing temperature. The specification also lists AASHTO M-85 high early strength cement (Type III) for spall repairs (Ziegler and Levi, 2008). The Iowa DOT requires a maximum slump of 4 inch as well as 6.5% air entrainment; this specification does not require a minimum working temperature but instead requires the patching material to be at least 65 °F prior to placement. Table 5 lists the additional requirements of Minnesota's bordering states for partial depth repairs.

Table 5: Additional requirements by state

State	Additional requirements to the ASTM C928 specification
Iowa	Maximum slump of 4" 6.5% air entrainment No minimum air temperature but does requires the mix to be at least 65° F prior to placement
Michigan	Has no specification for partial depth repair
North Dakota	Maximum water content values given in a table Minimum air temperature 40° F Specifies ASTM M-85 high early cement for spall repair
South Dakota	Materials must reach 4000 psi @ 6 hours Spall repair to be done above 40° F
Wisconsin	Follows ASTM C928 with no additional requirements

Review of Previous Testing Studies for Patching Mixes

Several research studies have also focused on comparative evaluation of various CPR materials, such as a study by Cervo and Schokker, (2008). Factors such as cost, workability and durability are often used as evaluation parameters for making recommendations regarding the material selection. Several products were tested in the previous research projects. Different types of rapid set cementitious materials were considered. These include dry mix PCC concrete, magnesium phosphate cement, polymer concrete and polymer modified concrete (Cervo and Schokker, 2008, Markey et al., 2006, Good et al., 1993, Platte et al., 2009). The most common concrete mix in previous studies is based on the Type III Portland cement. Magnesium Phosphate has been used to accelerate set times and lower the permeability of the concrete (Cervo and Schokker, 2008). Polymer concrete is a composite mixture in which a polymerization of a monomer produces the bond between the cement and the aggregate added to the patch mixture. Polymer modified concrete is different in the fact that the synthetic polymer only replaces a portion, 10-15%, of the binding agent in Portland cement (Cervo and Schokker, 2008). The previous research studies that undertook laboratory tests on the CPR products typically included: compressive strength, flexural strength, set time, freeze-thaw resistance, abrasion resistance, and length change resistance measurements. The literature review also found three major field studies. The field study research was conducted in regions where the climate is warmer than that found in Minnesota. A study by the National Transportation Product Evaluation Program (NTPEP) was performed on a bridge deck in Ohio testing six different products (Platte et al., 2009). The Strategic Highway Research Program (SHRP) set up a field study covering four states: Utah, Arizona, Pennsylvania and South Carolina (Mojab et al., 1993). The Texas Transportation Institute's field tests were all conducted in Texas (Markey et al., 2006).

The NTPEP study tested the materials in 9 foot long by 3 feet wide by 4 inch deep patches. The edges were all saw cut with vertical faces. Materials included in the study are listed in Table 6.

Table 6: NTPEP Ohio bridge deck test materials

Manufacturer	Product name	Product type
Henkel Loctite	Fixmaster Magnacrete	Cementitious concrete
Quikrete Companies	Fastset DOT Deck repair Polymer with fibers	Polymer modified concrete
SpecChem	RepCon 928	Polymer modified concrete
W.R.Meadows	Sealtight Futura-15	Cementitious concrete
Willamette Valley Co.	FastPatch	Polymer concrete
CeraTech Inc.	Pavemend EX	Cementitious concrete

None of the products exhibited any spalling after 2 years. All of the materials showed mid-panel cracking of 1/32 inch except for the Willamette Valley FastPatch which had no mid-panel cracking. However the Willamette Valley FastPatch had the most edge cracking at 1/16 inch and showed 4% delamination. The most severe delamination occurred with the W.R. Meadows Futura-15, it was recorded at 66%.

The multistate SHRP study is one of the most extensive research projects on partial depth patching (Mojab et al., 1993). Ten different products were used and are listed in Table 7. Once the patches were in place they were evaluated at 1, 3, 6, 12 and 18 months. Distresses and severity were recorded. Failure was based on the serviceability of the roadway, and is subjective (Mojab et al., 1993). The results of patch failures are presented in Table 8.

Table 7: SHRP field test materials

Manufacturer	Product name	Product type
Generic	Type III PCC	Cementitious
United States Gypsum Co.	Duracal	Gypsum cement
Set Products Inc.	Set-45	Magnesium Phosphate cement
Five Star Products Inc.	Five Star HP	3 part epoxy grout
Sika Corporation	SikaPronto 11	2 part modified methacrylate
Accelerated Systems Technology Corporation	Penatron R/M-3003	2 part flexible polyurethane
Lone Star Industries Inc.	Pyrament 505	Cementitious
None provided	MC-64	2 part epoxy
GeoCHEM Inc.	Percol FL	2 part flexible polyurethane resin
Unique Paving Materials Corporation	UPM High Performance Cold Mix	Premixed bituminous

Table 8: Results of SHRP study

Material	% Failed
Pyrament 505	11.4
Percol FL	5.0
Set-45	4.3
Five Star HP	2.6
Type III PCC	1.2
Duracal	0
MC-64	0
SikaPronto 11	0
Penatron R/M 3003	0
UPM High Performance Cold Mix	0

Best Construction Practices Guidelines for Partial Depth Repair

A review of the best practices for partial depth repair was also conducted. A comprehensive list of the most important steps to perform for partial depth repairs is available from the Institute for Transportation located at Iowa State University. The list consists of nine basic steps to follow when performing partial depth repairs (D. P. Frentress and D. S. Harrington, 2012).

Construction of partial-depth repairs typically includes the following steps:

1. Determine repair boundaries.
2. Remove concrete.
3. Prepare repair area.
4. Prepare joint.
5. Apply bonding agent (do not allow to dry).
6. Place the patching material.
7. Apply curing compound.
8. Optional diamond grinding.
9. Seal joints

Summary

There have been many research studies conducted on rapid set patching materials. Some have covered a broad spectrum of climate conditions. However most of the research was intended to evaluate the products themselves, whereas this study intends to evaluate the current acceptance testing criteria in reference to performance of rapid set patches in cold climate pavements. Furthermore, the study will also identify currently used and new test procedures that are most relevant to the performance. Finally, a brief overview of the best practices associated with installation of partial depth patches using rapid set materials will also be discussed. The overarching intent is to ultimately save money by not having to conduct lengthy field testing of new products through use of a laboratory testing based acceptance criteria that focuses on tests that are most relevant to cold climate performance and can be easily conducted in laboratory.

Chapter 3: Testing and Results

Scope of Testing, Products/Materials

Testing at the beginning of the project consisted of six different tests: compressive strength gain, flexural strength at 4 hours, setting time, freeze-thaw durability, shrinkage and pull-out bond strength. The tests were performed by following the ASTM C928 specification for rapid setting, pre-bagged cementitious materials. The only deviation from that standard is the bond strength test, which is described herein.

Testing Procedures and Methodology

The initial tests of the project conformed to the ASTM C928 standard specification for testing rapid set materials. The tests and their corresponding ASTM designations are located in Table 9.

Table 9: Properties Evaluated and Preliminary Test Methods

Property	Preliminary Test Method
Set time	ASTM C191 – Standard Test Method for Time of Setting of Hydraulic Cement by Vicat Needle
Strength gain	Time interval testing (3 hours, 24 hours, 7 days and 28 days) using ASTM C 39 – Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens
Flexural strength	ASTM C78 – Standard Test Method for Flexural Strength of Concrete (at 4 hours)
Shrinkage	ASTM C490 - Standard Practice for Use of Apparatus for the Determination of Length Change of Hardened Cement Paste, Mortar, and Concrete
Bond strength	Modified version of ASTM C900 – Standard Test Method for Pullout Strength of Hardened Concrete
Freeze-thaw durability	ASTM C666 - Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing

Setting Time

The ASTM C191 is the standard test of setting time for hydraulic cement using the Vicat Needle apparatus. The testing of set times is crucial for determining the working time of concrete (Koehler and Fowler, 2003). The results of this test are the initial set time and the final set time. The initial set time is the critical because it is the point at which a product has begun to set; this indicates the end of workability. Final set time is the point at which a material becomes fully set on the surface. The Vicat needle apparatus pictured meets ASTM specifications (Figure 3).

Figure 3: Vicat needle apparatus

Strength Gain

Compressive strength gain measurements were obtained using the ASTM C39 standard test. The cylinders used during this test were eight inches long and four inches in diameter. The tests were conducted at time intervals of 3 hours, 1 day, 7 days and 28 days (Figure 4).

Figure 4: Compression Test Setup

Flexural Strength

The flexural strength was determined using the ASTM C78 test. The specimen for this test was a 6 X 6 inch rectangular beam eighteen inches in length. The beam is placed in the four point bending fixture and subjected to a force in the lateral direction, this causes a failure in flexure. The test was performed at 4 hours after the addition of water to the specimen. The result is the modulus of rupture which is an indicator of the flexural strength (Figure 5).

Figure 5: Four-point Bending Test Fixture in Compression Frame

Length Change

Shrinkage testing was done using the ASTM C490 standard. Samples are cast in 2 X 2 X 11 inch prisms and then measured at 3 hours and 28 days to determine the amount of length change that they experience in that time frame. Length change is important because it can directly affect the bond between the patch and the pavement slab. The larger the amount of expansion or contraction a material exhibits the more likely the patch will fail due to breaking of the bond interface.

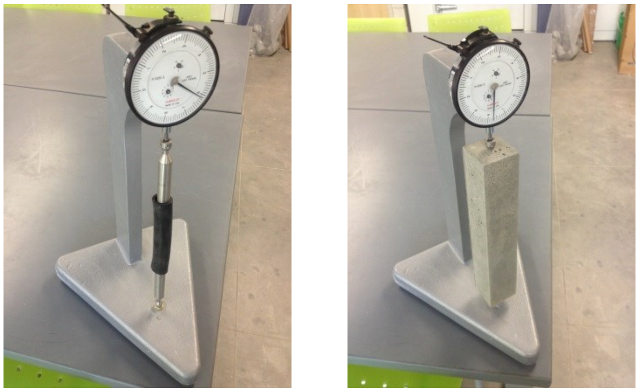
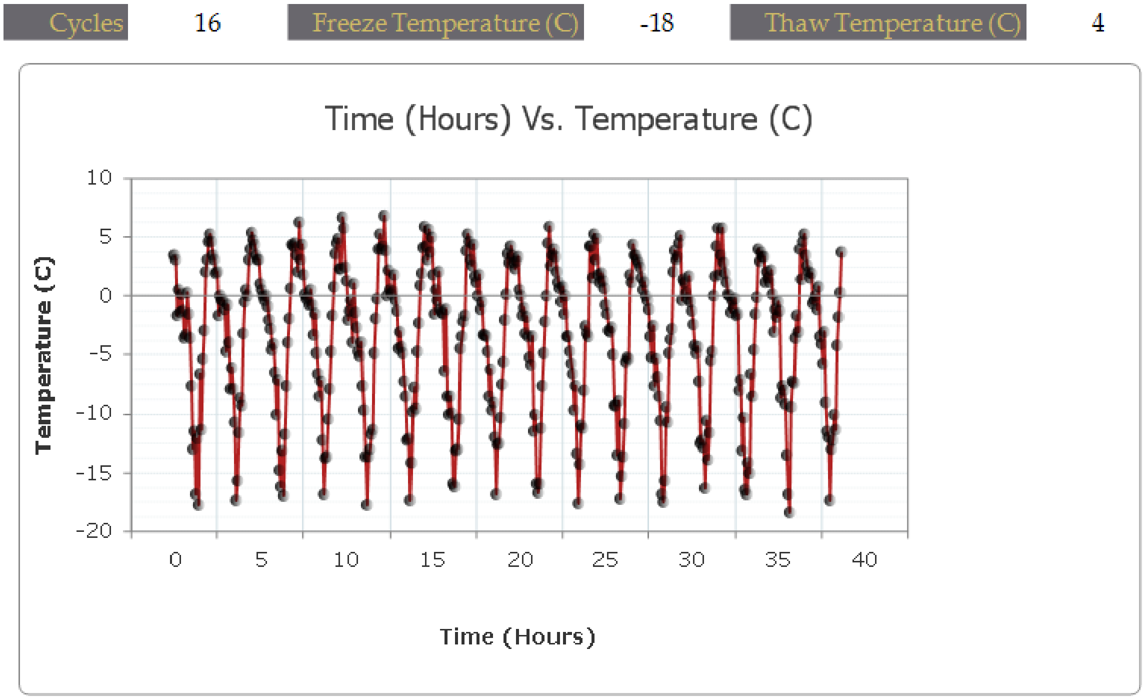


Figure 6: Length Change Measuring Device with the Standardized Bar and Test Specimen

Freeze Thaw / Durability Factor

The ASTM C666 test for rapid freeze-thaw is a cyclic test to measure durability of the material in cold climates. Data from this test indicates how resistant the concrete material will be to rapid temperature swings in the field. Considering the climate in Minnesota the need for this test is apparent.

The durability factor is calculated using fundamental transverse frequency data of each specimen which is collected by an E-meter. Fundamental transverse frequency involves impact theory; the specimen is struck with a metal mallet which creates a shock wave that travels through the material at a certain fundamental transverse frequency. The stiffness of the material is determined by how fast the shockwave travels through the material, the shockwave speed is indicated by its frequency. The fundamental transverse frequency is then used to calculate the dynamic modulus. The frequency data collection was done at an interval of 16 freeze-thaw cycles (Figure 7). The E-meter used for collecting this data can be seen in Figure 8.



Cycles 16 Freeze Temperature (C) -18 Thaw Temperature (C) 4

Figure 7: Typical plot of cycles from the freeze thaw chamber

Figure 8: E-meter used to collect frequency data

Figure 9: Freeze-Thaw Chamber and Digital Control Box

Slant Shear Bond Test

The ASTM C882 slant shear test is used extensively for bond strength (Pattnaik, 2006). The test was found to not be repeatable on a regular basis. Several of the composite cylinders tested in previous research programs did not break along the slanted interface which led to different bond strengths for the same material (Pattnaik, 2006). The geometry of the slant shear test involves a normal force that results in higher bond strengths because some of the force exerted by the testing apparatus does not directly load the bond (Ferraro, 2008). This normal force produces a friction force that is not representative of the actual failure mechanism (Trevino et al., 2004). The schematic of slant-shear bond test is shown in Figure 10. This test was intended for testing various epoxies that can be used to bond two concrete faces to one another.

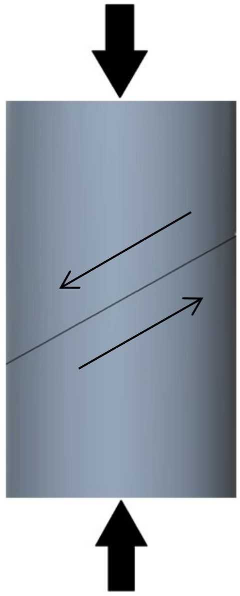


Figure 10: Schematic of the Slant Shear Bond Test

Modified Bond Strength Test

The bond strength is the only test performed during the initial portion of the project that deviates from the ASTM C928 specification. The test to be used in our lab is an adaptation of the ASTM C900 pull out test. An adaptation was made because the ASTM

C900 is a test of the pullout strength of a homogenous section of concrete and is generally intended for testing anchorages.

The setup for this adaptation included a 12 X 12 inch slab 3.5 inches thick that had a 3 inch hole bored through the center. A threaded rod was then cast into the bore hole with the product being tested. The threaded rod was ½ inch hardened steel which was anchored on the bottom of the slab with a 2 ¾ inch washer and lock nut, this was done once the rapid set material was set.

The slab with the threaded rod was then placed into an MTS frame and subjected to tension. The entire surface of the slab was supported by ½ inch plate steel inside of the structure in Figure 11. A displacement rate of 4 millimeters per minute was used rather than a load rate of force per time.

Figure 11: Bond Pullout Testing Fixture in the MTS Machine

A rendering of the specimen to be used for the adapted bond pull-out test is shown in Figure 12. Results from this test are qualitative and used for comparison purposes only. The values obtained are not an indicator of the longevity of the patching material.

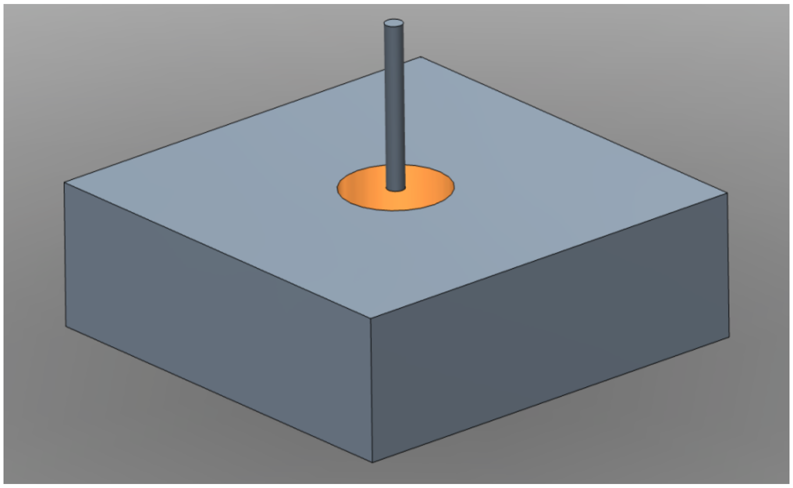


Figure 12: Pull out apparatus schematic

A finite element model (FEM) was made of the test specimen to verify the results and failures that were observed from actual testing. The load was placed in the model on the interior surface of the boring while the supports were placed on three sides of the slab to simulate the actual test set up. The steel plate and concrete slab were modeled as separate bodies. The simulation was performed with a computer generated mesh size of one inch (Figure 13).

The results of the FEM simulation show the stress concentrations in the material (Figure 14). The stress around the bore hole of the model is approximately 1200 psi. This is sufficient to break the slab in flexure.

The maximum deformation location from the model is consistent with the starting point of the actual failures that were observed (Figure 15). The scale in the graphic is exaggerated so that the deformation could be seen.

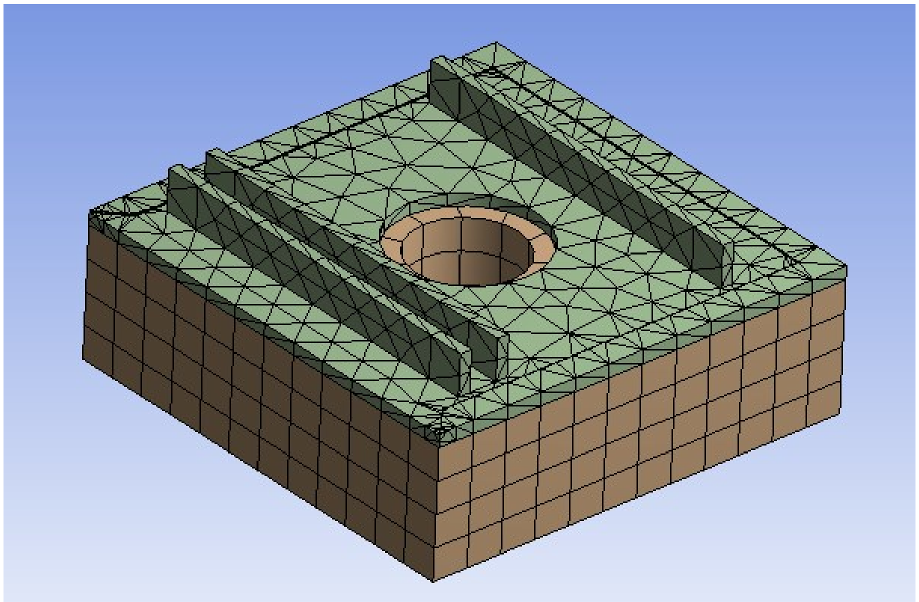


Figure 13: Meshing used in the FEM simulation

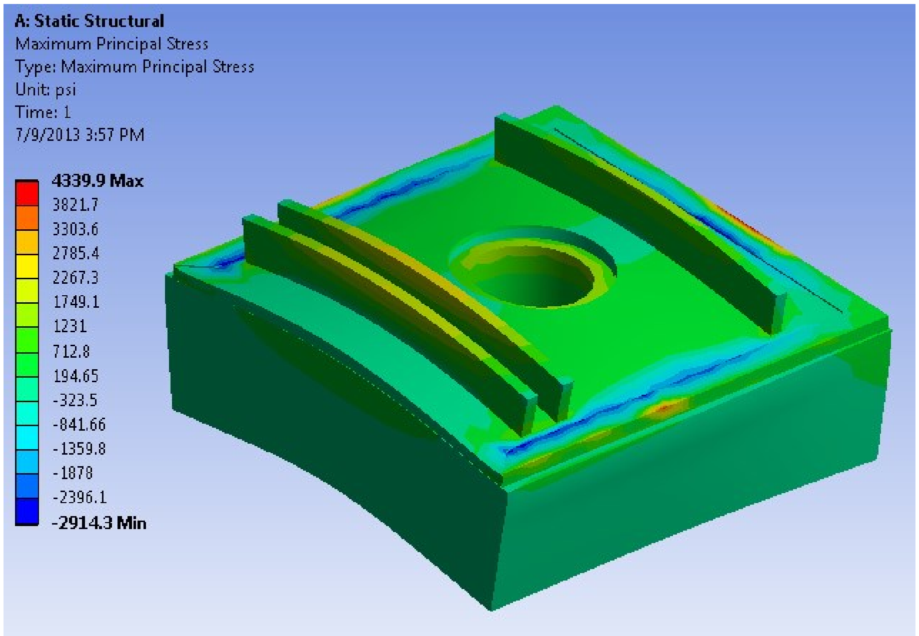


Figure 14: Maximum principle stress from finite element analysis

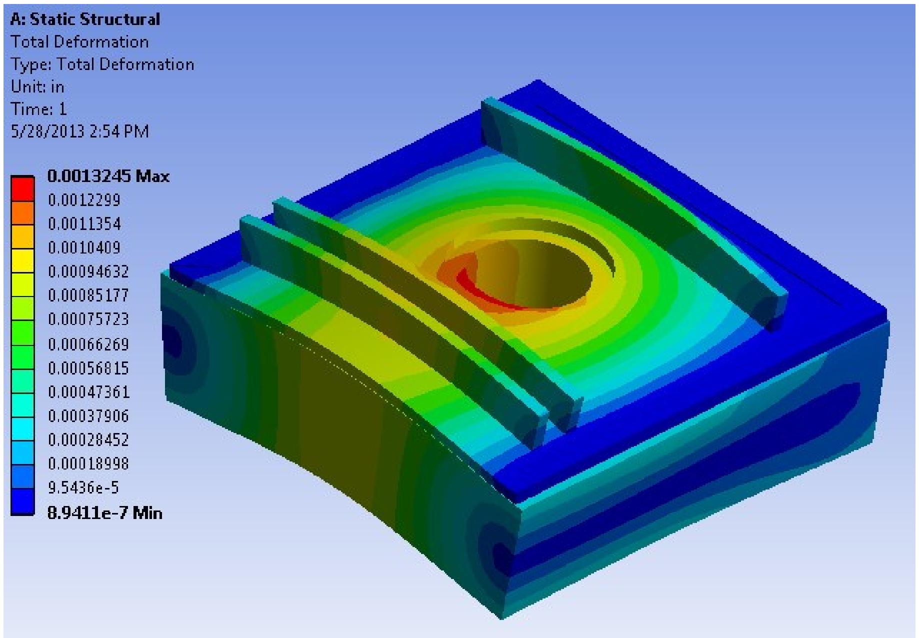


Figure 15: FEM deformation results

Laboratory Mixing and Specimen Preparation

Mixing instructions for each product were provided from the product manufacturers or mix developers. All specified gradations, proportions and water amounts were adhered to. The extremely rapid setting materials were mixed using a drill and paddle in five gallon buckets. These products included: Pavemend SL, Pavemend SLQ, Mono Patch, Futura-15 and the Rapid Patch Taconite mix. The remaining materials were mixed in a small concrete mixer.

Figure 16: Drill and paddle with a bucket and a standard concrete mixer

The materials were comprised of both proprietary mixes and mixes that required additional proportioning. Proprietary mixes included; 3U18, 3U18M, Futura 15, Futura 45, Mono-Patch, Pavemend SL, Pavemend SLQ, Rapid Set Concrete Mix and TCC Taconite Mix, these only required the addition of water. The TCC Taconite mix had mixing liquid included (manufacturer provided water premixed with activator). Materials also came bagged as cementitious materials and required admixtures as well as additional aggregates, these included; District 3 Mix 1 and 2, FiveStar Highway Patch and Akona. Admixtures included super plasticizer/accelerator and air entrainment liquids. The aggregate used for the MnDOT District 3 mixes was provided by MnDOT District 3. The Akona Rapid Patch and the Five Star were extended using locally sourced aggregates. The gradation of the local coarse aggregate is MnDOT CA-50 (MnDOT Standard Specification for Construction, 3137).

Testing Results

Compressive Strength Gain

The data in Figure 17 represents the compressive strength of each mix at 3 hours, 1 day, 7 days and 28 days on a log scale axis. Take note that in general the mixes that started below 1000 psi at three hours made large gains over time, in some cases by over 1000 percent. These mixes are the products that are Type III cement based. Also note that the products that achieved a compressive strength above 1000 psi at three hours on average doubled in strength at twenty eight days.

When Portland cement concrete goes through the hydration process it forms crystals which ultimately give the concrete its strength. This can be thought of as a bond matrix. The patching materials that have very rapid strength gain hydrate more quickly and therefor develop a shorter bond matrix. Because of this the ultimate compressive strength gain will be lower than the products that require more time to hydrate.

Considering the ultimate compressive strength as a measure of the quality of a patching material can be misleading, further discussion of this topic is located in the freeze thaw section. A patch material that reaches a compressive strength sufficient enough to support traffic is the goal.

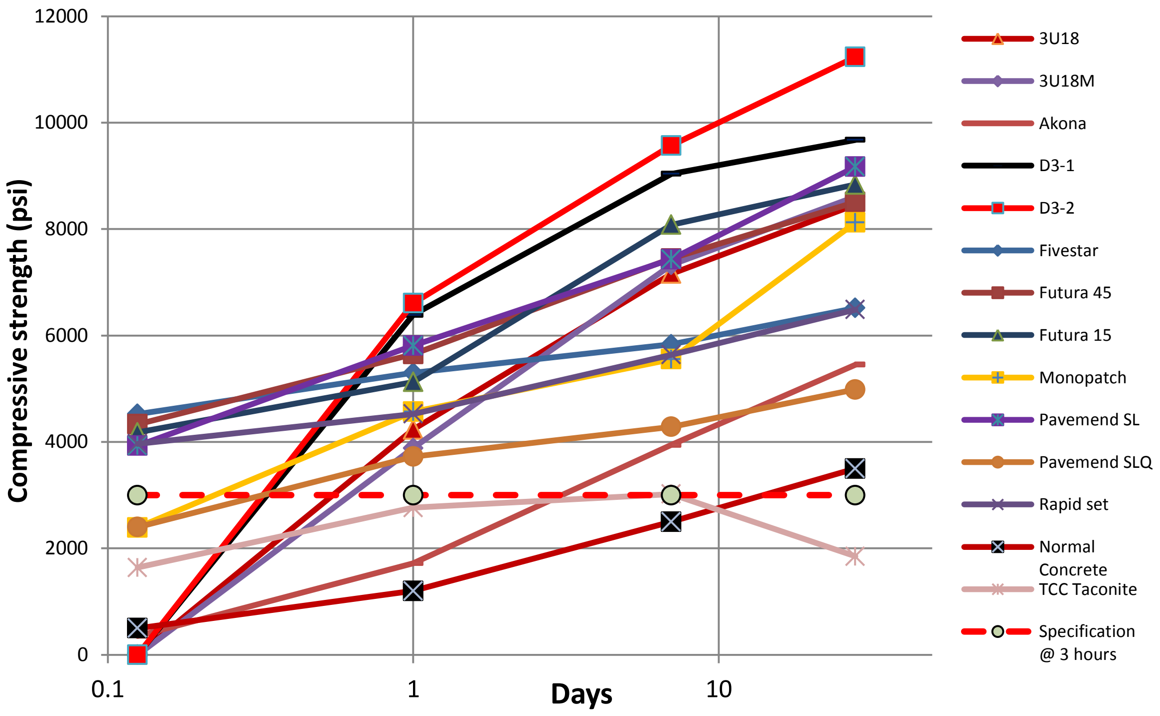


Figure 17: Compressive Strength Gain Results

The values in Table 10 illustrate the percentage of ultimate strength gained at each of the data collection times. This is another indication of how quickly a material gains compressive strength.

Table 10: Compressive Strength Gains at 3 hour, 1 day and 7 day (expressed as percent of 28 day compressive strength)

Product	28 Day Comp (psi)	3 Hour (% of 28 Day)	1 Day (% of 28 Day)	7 Day (% of 28 Day)
3U18	8463	-	50.0	84.6
3U18M	8610	-	45.1	85.1
Akona	5454	6.5	31.5	72.4
District 3 Mix 2	11236	-	58.8	85.2
District 3 Mix 1	9677	-	66.0	93.4
Five star	6518	69.5	81.3	89.5
Futura 15	8838	47.3	58.0	91.5
Futura 45	8509	50.9	66.4	87.5
Mono Patch	8126	29.4	56.2	68.4
Pavemend SL	9172	42.8	63.4	81.1
Pavemend SLQ	4985	48.2	74.7	86.0
Rapid Set Concrete Mix	6488	61.1	69.8	86.9
TCC Taconite	1852	88.4	149.0	163.0
Normal Concrete	3500	14.2	34.2	71.4

Flexural Strength/ Modulus of Rupture

The flexural strength measurement was recorded at 4 hours. The data in Figure 18 indicates that most of the products do not meet or exceed the modulus of rupture for normal concrete; however the concrete reading on this plot was measured at 28 days. Eight of the mixes reach at least 50% of the flexural strength of cured concrete in 4 hours.

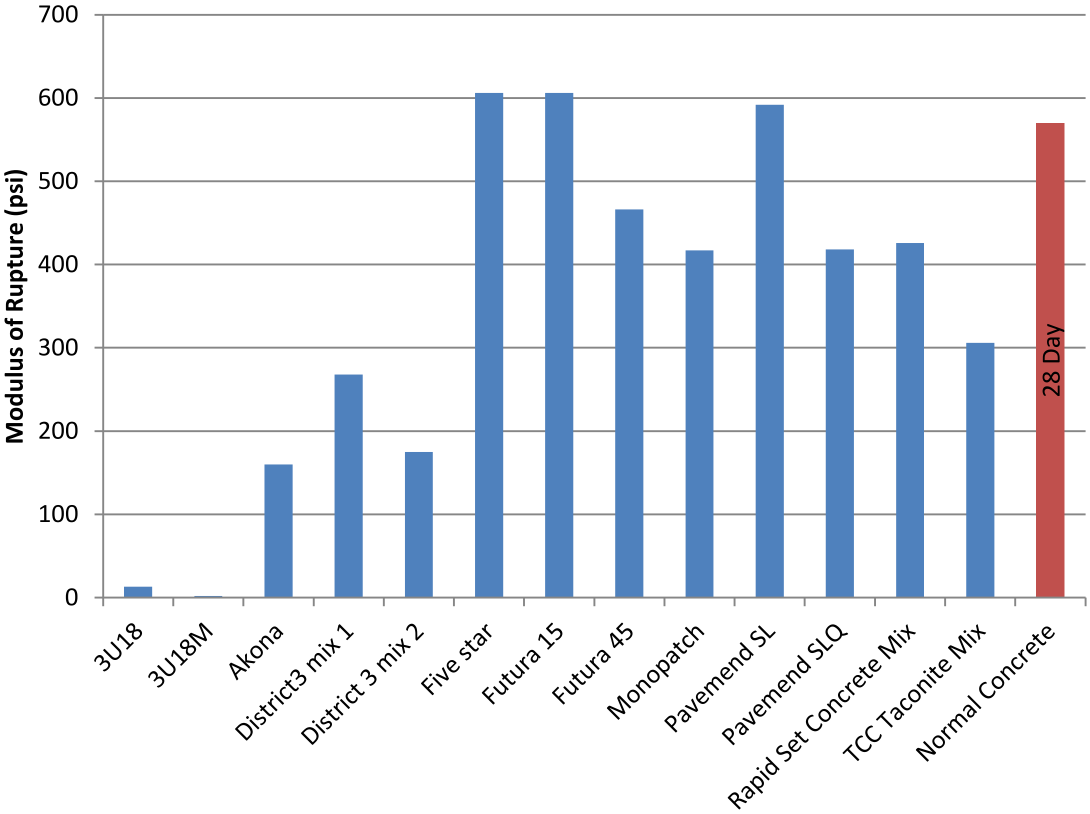


Figure 18: Measured Modulus of Rupture (Flexural Strength)

An estimation of the modulus of rupture from the compressive strength is presented in Table 11. Although the measured flexural strength was performed at four hours, the estimated value was based on the three hour compressive strength of each product. The estimation formula, $M_R = k\sqrt{f'c}$, was used for the calculations. The k is a multiplication factor that ranges from 7.5 to 10 (Mamlouk and Zaniewski, 2011, page 293). The *f'c* term is the compressive strength of the material. The minimum value in Table 11 was calculated using $k = 7.5$ and the maximum was calculated using $k = 10$.

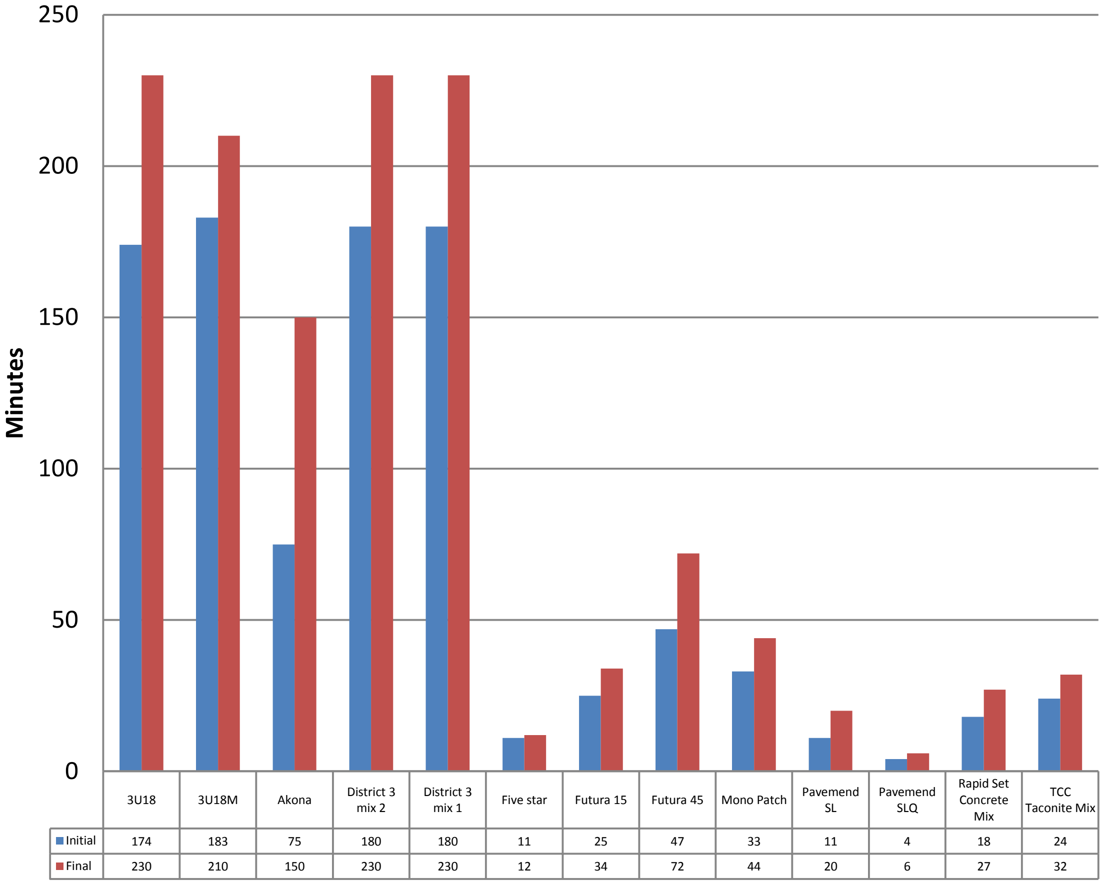
The estimation formula method was unsuccessful for two of the products; Futura 45 and Rapid Set Concrete Mix. Four products could not be estimated as they had no measurable compressive strength at 3 hours.

Table 11: Estimation of the Modulus of Rupture

Material	Modulus of Rupture (psi)		
	Estimated value (3hr.)		Measured value (4hrs.)
	Min	Max	
3U18	-	-	13
3U18M	-	-	0
Akona	141	188	160
District 3 Mix 1	-	-	268
District 3 Mix 2	-	-	175
Five star	505	673	606
Futura 15	485	646	606
Futura 45	494	658	***466***
Mono Patch	367	489	417
Pavemend SL	470	627	592
Pavemend SLQ	368	490	418
Rapid Set Concrete Mix	472	630	***426***
TCC Taconite	303	430	306

Setting Time

The setting time is an important variable to consider for choosing a rapid patch material when considering the amount of time required for opening a lane to traffic. The testing of set times is crucial in for determining working time of the concrete (Koehler and Fowler, 2003). This variable is not an indicator of overall patch performance or the longevity for a patch. Results from the actual tests can be found in Figure 19.



	3U18	3U18M	Akona	District 3 mix 2	District 3 mix 1	Five star	Futura 15	Futura 45	Mono Patch	Pavemend SL	Pavemend SLQ	Rapid Set Concrete Mix	TCC Taconite Mix
🟦 Initial	174	183	75	180	180	11	25	47	33	11	4	18	24
🟥 Final	230	210	150	230	230	12	34	72	44	20	6	27	32

Figure 19: Setting Times

Freeze-thaw durability

The freeze-thaw durability of concrete and mortars are typically expressed as a durability factor. Durability factor is a representation of how well a material resists rapid freezing and thawing cycles. As previously discussed the durability factor is determined by employing impact theory and recording the frequency of the shockwaves that propagate through a material.

The freeze thaw durability data contains two different extremes as can be seen in Figure 20. The overall trend is a durability factor between 15 and 25. Four of the products performed very well in comparison to the others. Theoretically the durability factor should not be over 100. The Pavemend SLQ and the TCC Taconite Mix both finished over 100 which indicated that they cured significantly after being placed into the freeze thaw chamber. The materials were placed into the chamber after curing for 14 days as per the ASTM C666 specification.

*Note that the normal concrete durability factor was measured on a sample that had 5.5% air entrainment.

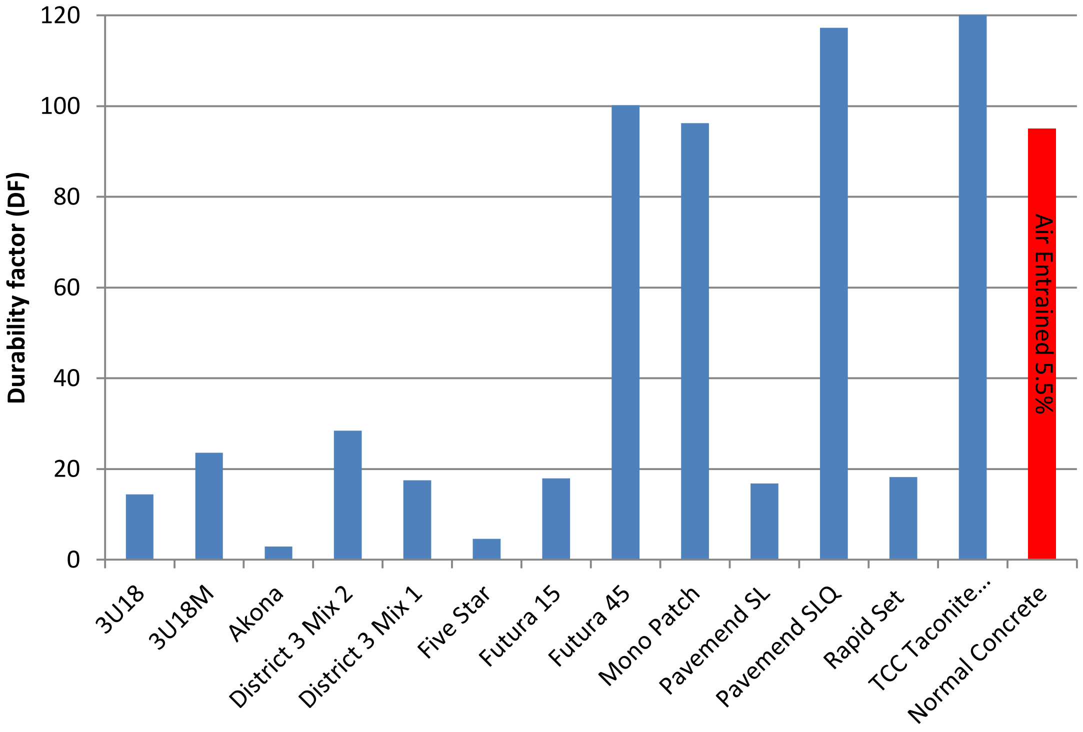


Figure 20: Freeze-Thaw durability factors

A plot of the change in the relative dynamic modulus (RDM) compared to the number of cycles shows how the dynamic modulus changed over time (Figure 21). Each cycle in the freeze thaw chamber represents approximately 3 hours. During the 3 hour cycle the specimen is heated to 4°C and then cooled to -18°C.

The RDM is a measure of the current dynamic modulus compared to the material's initial dynamic modulus. The results of the freeze thaw test show the ability of a material to retain its dynamic modulus. This is NOT an indicator of which material has greater or lower modulus than the others.

Note that all of the products show an increase in relative dynamic modulus, this occurs due to the materials being submerged in water during the test. The excess moisture that was available provided an environment that allowed the materials to hydrate further which increased the stiffness of each material. Eventually the material's relative dynamic modulus begins to decrease, this is an indication that the internal bonds are beginning to break down. The breakdown of the internal bonds is caused by internal pressure build up caused by infiltrating water that freezes during the cycles.

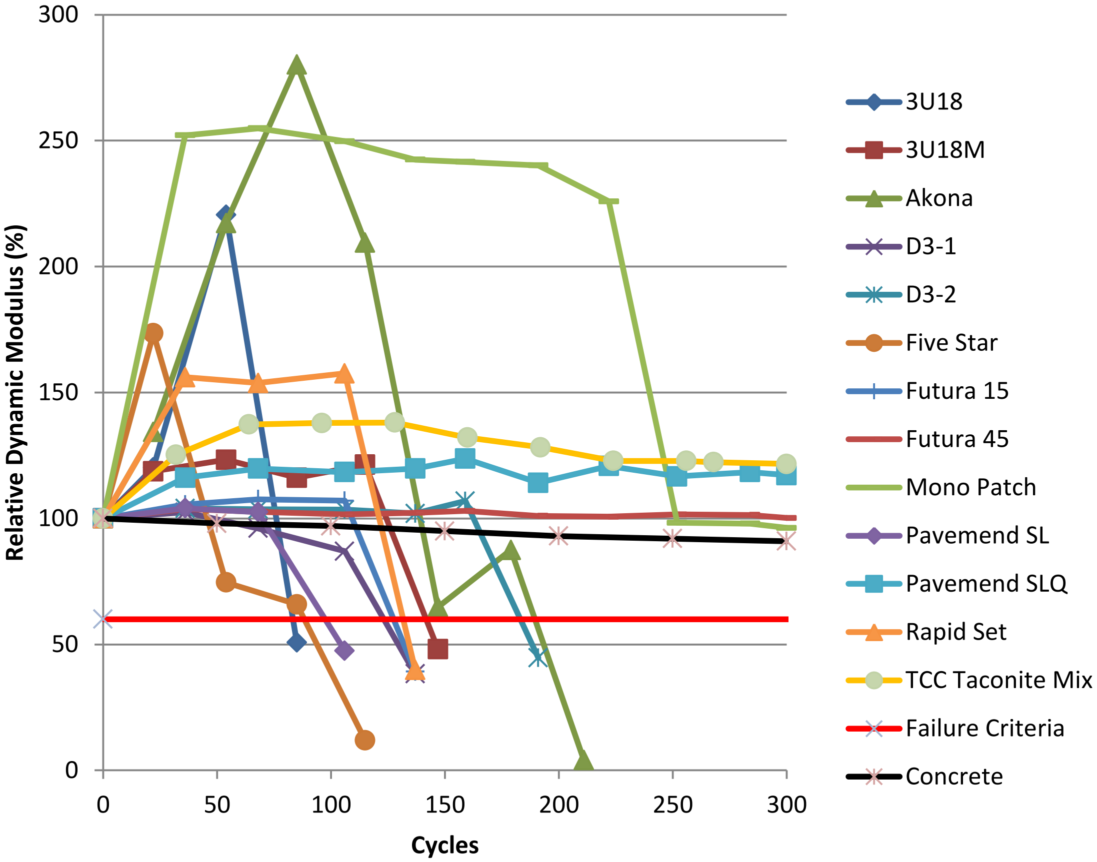


Figure 21: Fluctuation of the RDM vs. the number of cycles spent in the freeze-thaw chamber

In order to compare the actual stiffness of each material to one another the dynamic modulus must be calculated from the fundamental transverse frequency. To realize the effects of freeze thaw the dynamic modulus is plotted versus the number of cycles in Figure 22.

The data series that have black markers are the products that reached the maximum allowable number of cycles during the ASTM C666 freeze thaw test. Solid black lines indicate the four products chosen to move forward for more extensive testing procedures.

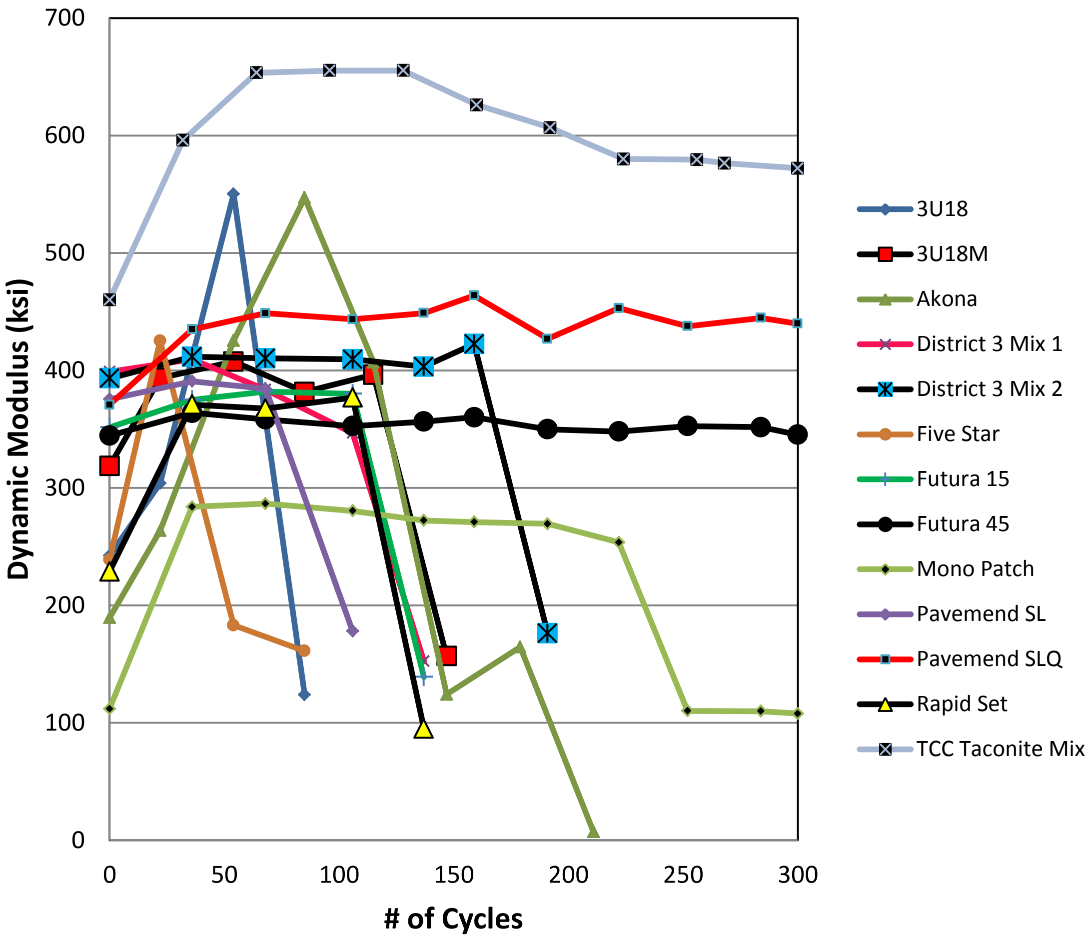


Figure 22: Dynamic modulus vs. the number of freeze thaw cycles

The change in mass of each product was also recorded (Figure 23). This measurement did not directly correlate with the RDM change for the same number of cycles. Some materials lost mass while maintaining their RDM as they went through freeze-thaw cycles. In some instances the mass loss was quite substantial. Thus, it can be summarized that the measure of material durability only in terms of RDM might be inadequate and the loss of mass should also be considered in the evaluation of patching mixes. There were materials that gained mass throughout the freeze thaw process; one theory is that those products were producing gypsum as part of the curing process. The data for the normal concrete was obtained from a study done by the Federal Highway Administration (FHWA, 2006).

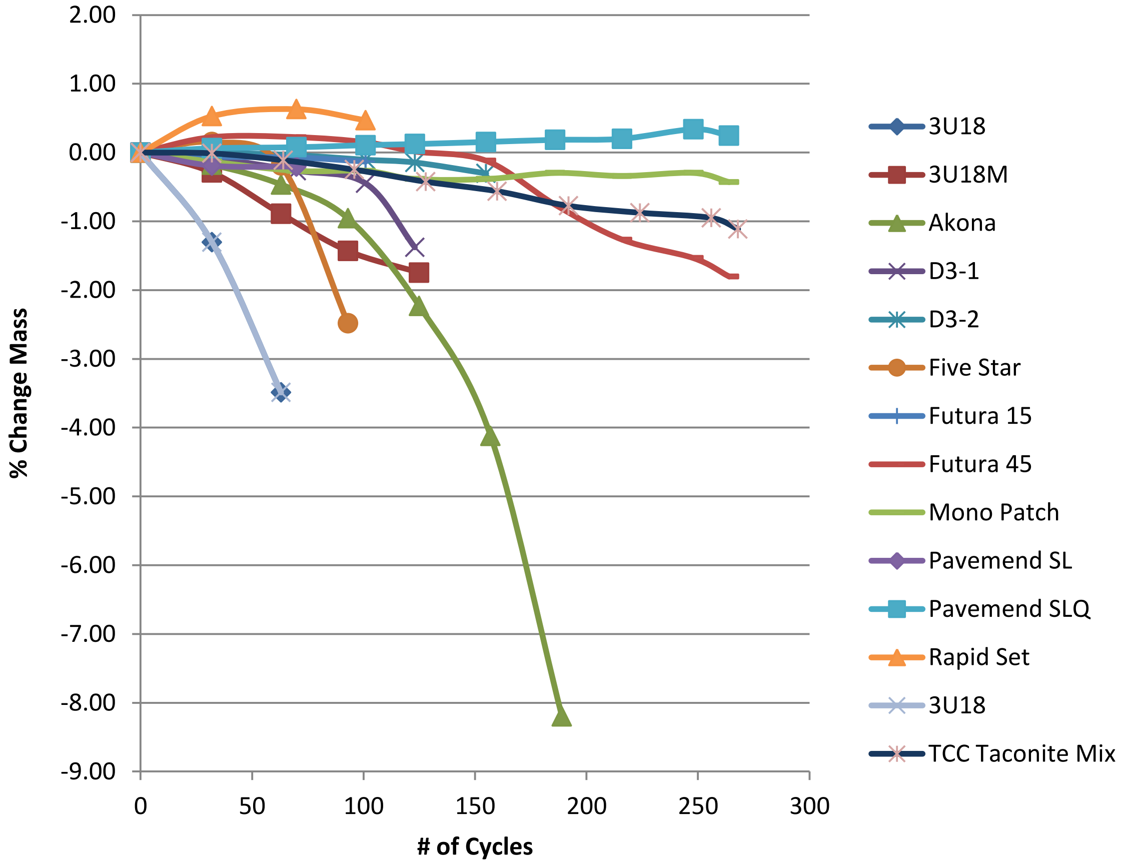


Figure 23: Percent change in mass vs. the number of cycles

Another important aspect to consider is that a high compressive strength does not necessarily indicate that a product or a material will have good freeze thaw durability. A comparison of the durability factor and the 28 day compressive strength is shown in Figure 24. This shows that some products having relatively high compressive strengths were found to have low durability factors. This can be seen in particular with the TCC Taconite Mix which had the lowest compressive strength while at the same time exhibiting the highest durability factor.

There is a correlation between compressive strength and durability factor when considering the Portland cement based products. The products on the left side of the plot do follow a relatively linear correlation, as the compressive strength increases so does the durability factor. The 3U18M contains a premixed air entrainment admixture which explains the slightly higher durability factor. No formulation was provided for the Rapid Set, making the explanation for its increased durability factor difficult.

Note the four products that were near or above durability factor of 100 ranges in compressive strength from 1852 psi to 8509 psi. This confirms that compressive strength is not a reliable indicator of freeze-thaw durability.

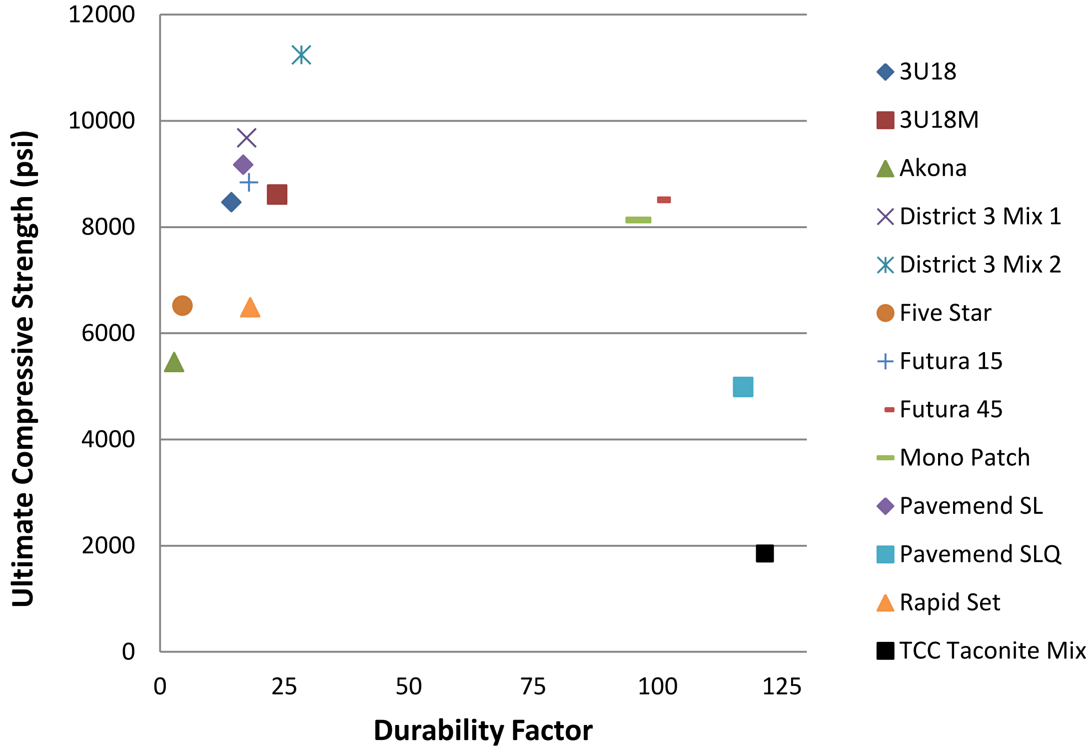


Figure 24: Durability Factor vs. Ultimate Compressive Strength

Most of the products lost mass during the freeze thaw process which was expected; however two of them did gain a minimal amount. The plot in Figure 25 shows that the percent change in mass could not be correlated with compressive strength. The scale for the percent mass loss is in reverse order to better depict the results that were observed. Mass losses of zero would be considered optimal. As can be seen, some of the materials reached over 8,000 psi of compressive strength but lost more than 2% of their mass.

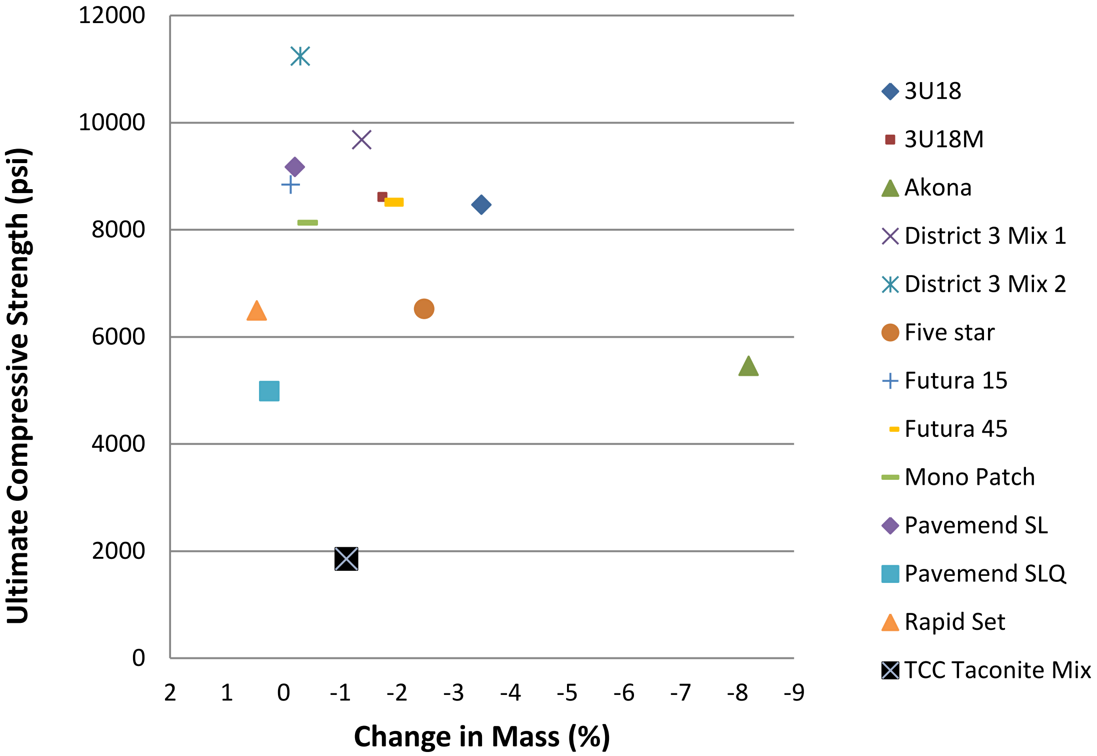


Figure 25: Percent Change in Mass vs. Ultimate Compressive Strength

The plots in the previous two figures are an indication that when choosing mechanical properties of materials it is best to view them as a whole. The ultimate compressive strength should not be considered as a telltale sign of patch performance.

Shrinkage (Length Change)

Length change yielded two unique results. There are two products that expanded while curing in air. Both of those products are magnesium phosphate based. Magnesium Phosphate has been used to accelerate set times and lower the permeability of the concrete (Cervo and Schokker, 2008). There were two products that failed to meet the

ASTM C928 specification; Mono Patch and the TCC Taconite mix. Mono Patch expanded in water beyond the limit, which is shown as the black line on the plot (Figure 26). The TCC Taconite mix exhibited shrinkage in both air and water. The excessive shrinkage of TCC Taconite mix is partly due to thermal contraction of the specimen as the material hardened at relatively high temperature (approximately 130 °F). The length change in water was within the limit for this material; however the shrinkage in air could not be accurately measured due to the fact that it was no longer within the limits of the testing apparatus.

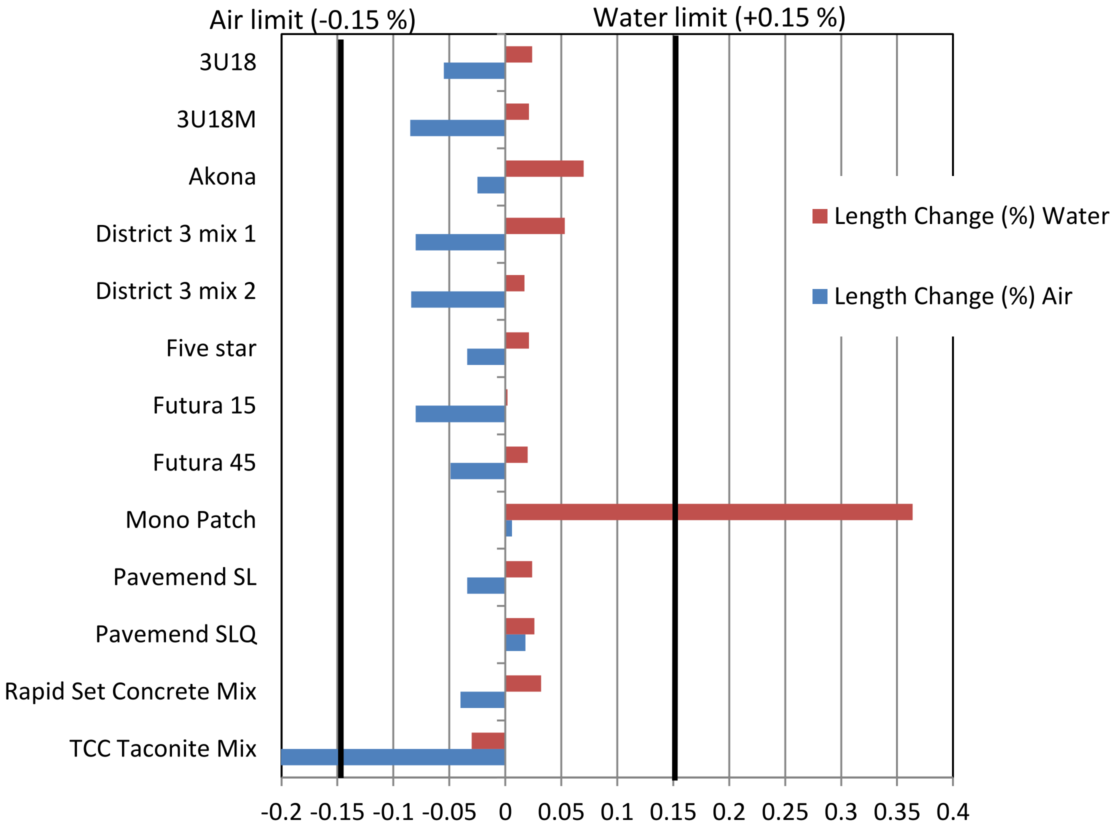


Figure 26: Length change in air and water at 28 days

Bond strength

The modified ASTM C900 bond strength test yielded results that suggest that the physical bond between the materials and the slabs is not an area of concern. Seven of the thirteen mixes carried enough load to break the slab before the bond interface failed. The results of this test are inconclusive as to whether or not it should be added to the testing regimen for rapid set patching materials. There was variability in the results obtained for two replicate tests of the same product. The loads achieved at the initial break of either the slab or the bond interfaces are in Figure 27. Included for the purpose of comparison is a sample of normal concrete and asphalt. In general, the loads were relatively high and thus in an overall sense it can be observed that bond failure of the patching mixes in shear/sliding mode may not be of concern.

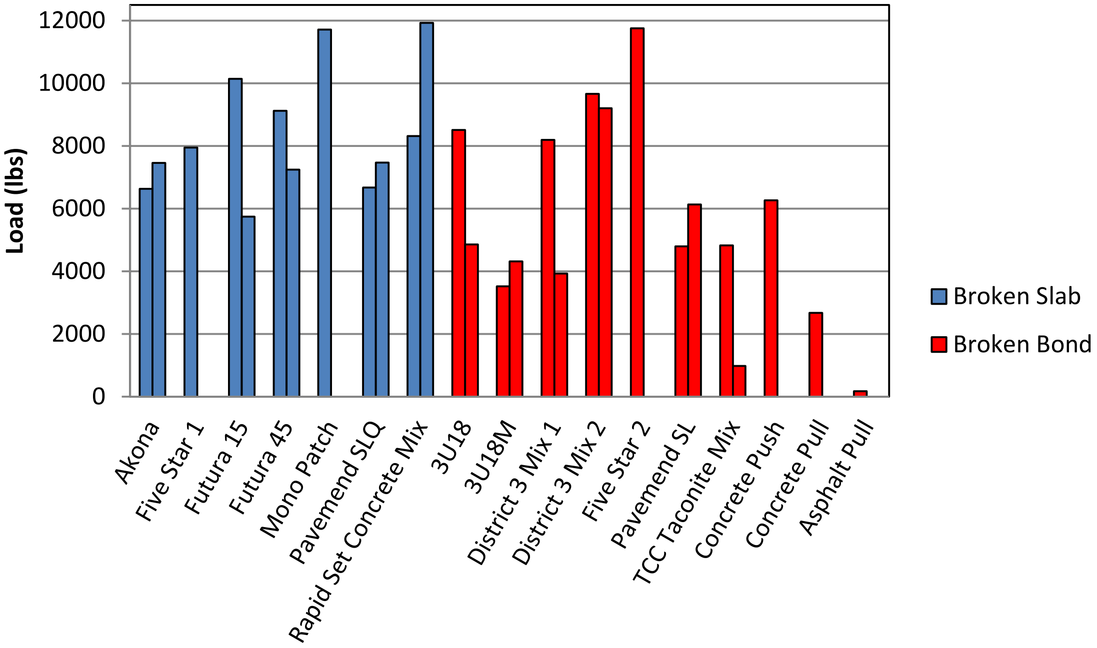


Figure 27: Load that caused the initial breakage of either the slab or the bond

Performance Review

Each of the thirteen products possesses qualities which are conducive for use as patching materials. There are many important properties to be considered for the use of any material. This study is intended to determine which products possess these properties prior to their acceptance as patching materials. Thus far the standard acceptance testing has been conducted with additional testing to follow. This is a discussion about the results of the current acceptance criteria.

The list of materials stated here is alphabetically tabulated and is in no way a reflection of a ranking system. The testing procedures for the project will include the items that are suggested by the ASTM C928 specification as well as a flexural pop-out test.

MnDOT 3U18

Mixing instructions were followed as per the manufacturer's specifications. The mix was held to a one inch slump which made workability low. Liquid admixture was used to achieve 5.5% air entrainment.

This mix fails to meet the compressive strength and slump requirement set forth by the ASTM C928. The flexural strength was the lowest of the products that could be measured. Freeze thaw durability ranked the third lowest among all products.

Figure 28: 3U18 compression, freeze thaw and pull out specimens

MnDOT 3U18M

This product contains an air entrainment admixture within the pre-bagged cementitious mix. It is much the same as the standard 3U18.

There are similar failures of the ASTM C928 spec, compressive strength and slump. The formed beam specimens for flexural strength were unable to support their own weight at four hours.

Figure 29: 3U18M compressive, freeze-thaw and pull out specimens

Akona Rapid Patch

This product is listed by the manufacturer as gypsum based cement. When cured the surface was smooth and shiny.

Compressive strength at three hours was negligible as the molded cylinders could not carry load. The flexural test did yield results; however, the interior of the beam specimen was still moist. The freeze thaw durability was the lowest among all products.

Figure 30: Akona compressive, freeze-thaw, flexural and pull out specimens

MnDOT District 3 Mix 1 (3U18 based)

A proportioned mix developed by Dan Labo at MnDOT District 3. This contained calcium chloride as well a liquid plasticizer admixture.

The mix did not achieve ASTM C928 specified strength requirements. When broken during the flexural test there was sufficient internal bond developed to break individual aggregate pieces even though the interior was still moist.

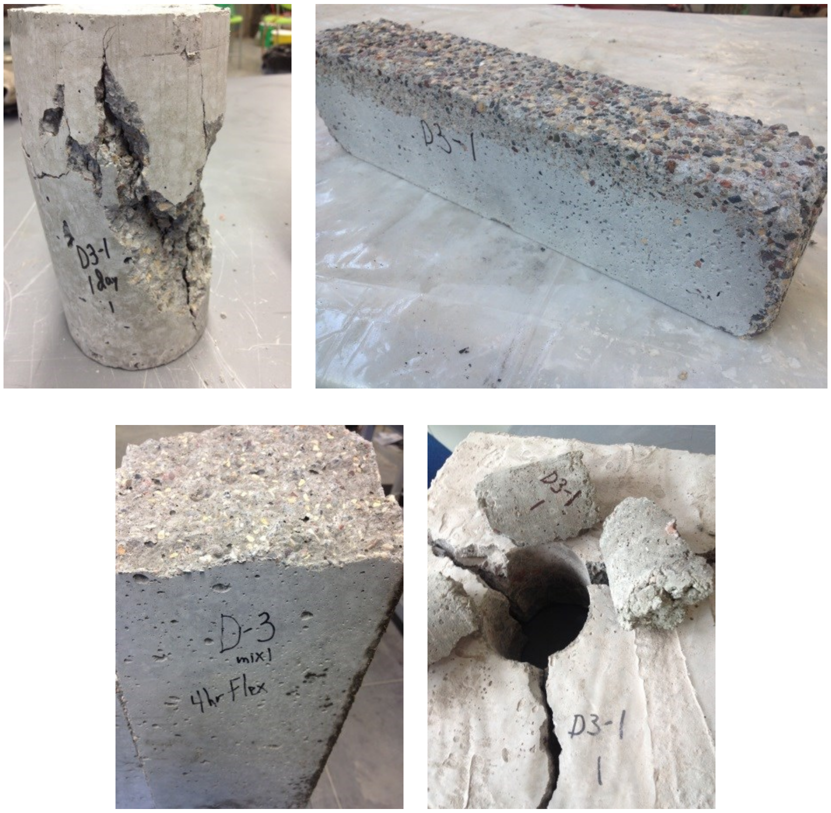


Figure 31: MnDOT District 3 Mix 1 compressive, freeze-thaw, flexural and pull out specimens

MnDOT District 3 Mix 2 (3U18 based)

This mix design is close to the MnDOT District 3 Mix 1. The difference being that micro silica comprises 5% of the cementitious material.

Once again the compressive strength was insufficient at three hours. This mix did achieve the highest overall compressive strength at twenty eight days, over 11,000 psi. At four hours the flexural strength test proved that the internal bond was present and aggregate was broken. The interior as well as the exterior was moist at the time of the flexural test.

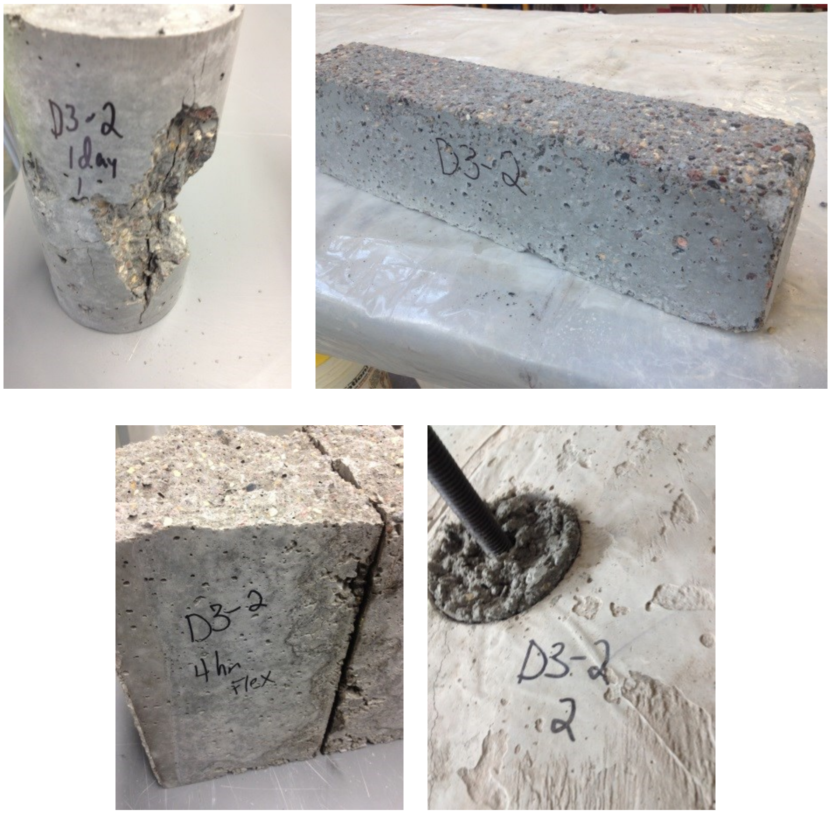


Figure 32: District 3 Mix 2 compressive, freeze-thaw, flexural and pull out specimens

Five Star Highway Patch

This mix starts off smooth and shiny, much like the Akona, but upon curing it takes on a low luster and becomes rougher. The cementitious material of this product is not listed by the manufacturer.

Strength gain at three hours was the highest among all products. Five Star also achieved the highest modulus of rupture at four hours. When broken for the flexural test the interior was completely dry and set. The resistance to freeze thaw was the second lowest of the group.

Figure 33: Five Star compressive, freeze-thaw, flexural and pull out specimens

Futura-15

The composition of this product was not disclosed by the manufacturer. The mixing, workability and finishing was similar to normal concrete.

Three hour compressive strength was among the top performers of the group. Even though it had achieved over 3,000 psi at three hours the interior of the cylinder molds was moist. It also displayed great compressive gains at 28 days. The modulus of rupture was the highest of the group and contained broken aggregate with a dry interior. Freeze thaw durability factor was below twenty.

Figure 34: Futura-15 compressive, freeze-thaw, flexural and pull out specimens

Futura-45 Extended

This product was similar to the Futura-15 except it has a longer set time. A slump of nine inches made workability easy.

Compressive strength gain was virtually identical to the Futura-15. The modulus of rupture was among the top performers. What set this apart was a large durability factor associated with freeze thaw resistance.

Figure 35: Futura-45 compressive, freeze-thaw, flexural and pull out specimens

Mono Patch

This is a magnesium phosphate based proprietary product. Workability was high with a 7¾ inch slump. This mix produced a moderate amount of heat during the curing phase; the specimens reached a temperature of 116°F at three hours.

Compressive strength at three hours was below the ASTM C928 specification. Modulus of rupture was on the higher end of the overall group. When the flexural test was complete the interior of the beam was dry and set but the product contained several spherical voids ranging from 1/16 to 1/8 inches in diameter. This may have contributed to the higher freeze thaw durability. However this product exhibited a failure during the length change specification. It showed high amounts of expansion in water as well as slight expansion in air.

Figure 36: Mono Patch compressive, freeze-thaw, flexural and pull out specimens

Pavemend SL

This is listed as high alumina cement by the manufacturer. Workability was high, this is a self-leveling mix.

The compressive strength at 3 hours was above the 3,000 psi mark. There was a great increase in the compressive strength at 28 days, it attained over 9,000 psi. This mix had the third highest modulus of rupture and was dry and set on the interior of the flexural beam. Freeze thaw durability was on par with most others which were below twenty.

Figure 37: Pavemend SL compressive, freeze-thaw, flexural and pull out specimens

Pavemend SLQ

Specialty Products lists this proprietary mix as magnesium phosphate based. This mix also was a self-leveling product. Even though it had high workability, care had to be taken as the working time was three minutes.

Three hour compressive strength was below the ASTM C928 specification. It did however exceed the 3,000 psi level at one day. This product has high freeze thaw durability with a durability factor above 100. The flexural strength was in the middle of the range for the group, when the beam was broken the interior was found to be dry and set. Like the Mono Patch, which was also magnesium phosphate based, this product expanded while curing in air as well as in water.

Figure 38: Pavemend SLQ compressive, freeze-thaw, flexural and pull out specimens

Rapid Set Concrete Mix

A Portland cement based product that most likely contains some accelerator given the fast setting times. Workability was high and the there was an adequate 15 minute working time.

Compressive strength gain was above the ASTM C928 specification. Freeze thaw durability was in the low range being below twenty. Flexural strength was in the middle of the group; the interior of the beam was dry and set.

Figure 39: Rapid Set compressive, freeze-thaw, flexural and pull out specimens

TCC Taconite Based Mix

The aggregate is from taconite tailings and the cementitious material is a product labeled as Akona. The mix also included a liquid component labeled as an activator which eliminated the need for mixing water.

The first attempt at mixing these components in the lab was not met with success. The product began to set up in the bucket while the mixing was still taking place. The following attempt was conducted outside on a day when the temperature was 31°F. The three components were placed outside for two hours prior to mixing. The plot in Figure 40 indicates a start temperature of 66 °F; this was due to the temperature increase that occurred during the mixing process. The resulting mixture yielded a more reasonable five minute working time. This product generates considerable heat while curing. It reached a temperature of 129°F thirty minutes after the liquid was added (Figure 40).

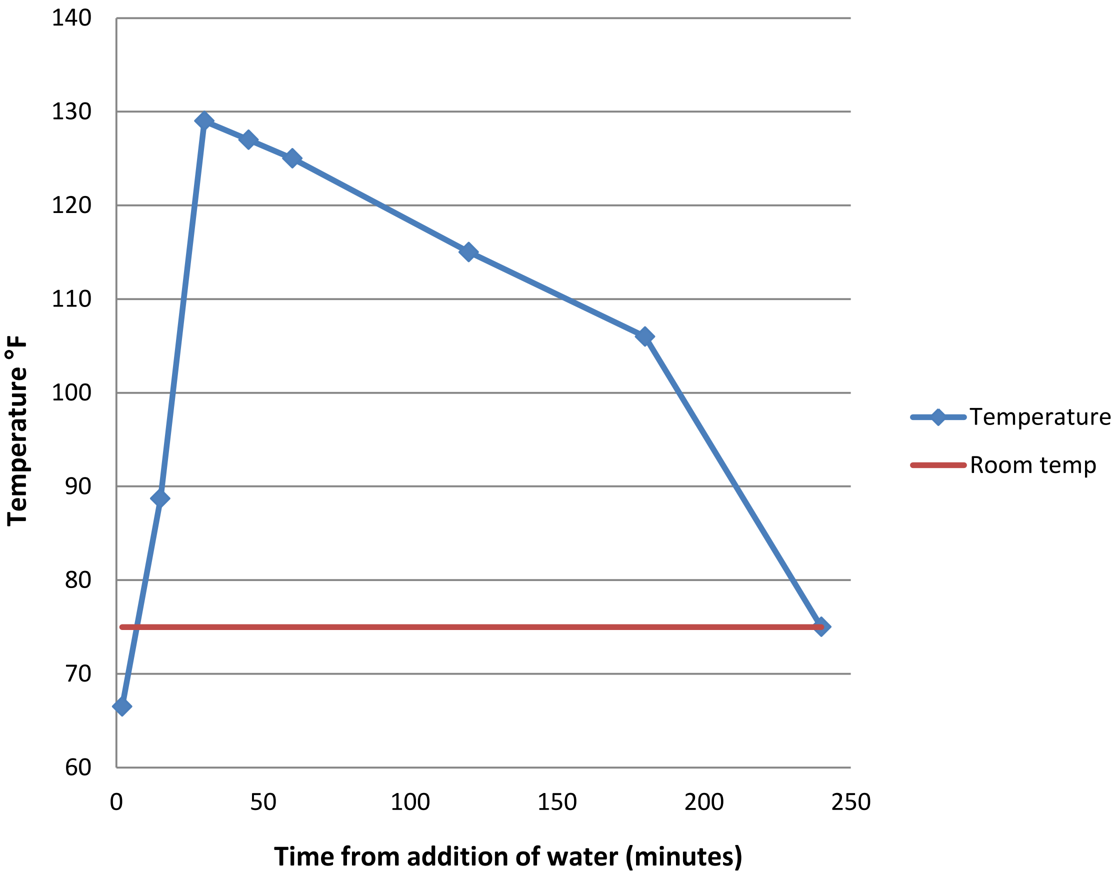


Figure 40: Heat of hydration for TCC Taconite Mix

Compressive strength at three hours was below the ASTM C928 specification. The 7 day strength was just above the MnDOT required minimum of 3,000 psi. Modulus of rupture was comparable to most of the other products. The interior of the flexural test beam contained several clay balls which were comprised of the taconite tailings aggregate.

These clay balls ranged from 1/8 to 1/4 of an inch and can be observed in Figure 41. The TCC Taconite Mix had the highest freeze thaw durability.

Figure 41: TCC Taconite mix compressive, freeze-thaw, flexural and pull out specimens

Product Comparisons

A listing of the products with their corresponding ranking for each of the following tests; 3 hour compressive strength, 28 day compressive strength, modulus of rupture, durability factor, shrinkage in air and expansion in water (Table 12). These rankings are based on actual data collected during the ASTM C928 standard specification tests.

Table 12: Ranking of the performance for the tested patching materials

Product	Rank Based on Testing Results					
	Short Term Compressive Strength (psi) (3 Hr.)	Compressive Strength (psi) (28 Day)	Modulus of Rupture (psi)	Durability Factor	Shrink age in air (%)	Expansion in H_2O (%)
3U18	Fails C928	7	12	11	8	7
3U18M	Fails C928	5	13	6	12	5
Akona	9	11	11	13	3	11
District 3 mix 1	Fails C928	2	9	9	9	10
District 3 mix 2	Fails C928	1	10	5	11	2
Five star	1	9	1	12	4	4
Futura 15	3	4	2	8	10	1
Futura 45	2	6	4	3	7	3
Mono Patch	Fails C928	8	7	4	2	Fails C928
Pavemend SL	5	3	3	10	5	6
Pavemend SLQ	6	12	6	2	1	8
Rapid Set Concrete Mix	4	10	5	7	6	9
TCC Taconite	Fails C928	Fails C928	8	1	Fails C928	12

RED = Failure of ASTM C928

YELLOW = Passes ASTM C928

GREEN = Top 3 performer among the group

Summary

The purpose for the testing during this project was to come up with a set of criteria for accepting and rating patching materials for partial depth applications. Careful consideration was given to the importance of the currently required testing procedures.

The unique application of patching materials requires a different ordering for the priority of certain mechanical properties compared to normal concrete uses.

- The importance of the modulus of rupture is not readily apparent. The estimation method of getting the (MOR) may be considered sufficient for the purposes of patching materials.
- Compressive strength data is imperative for patching materials. The amount of time required to reach 3000 psi compressive strength is of utmost importance, this indicates the amount of time required to reopen the roadways. The one and seven day compressive strengths are of little value to the ranking of patching materials. The rate of strength gain is important, but for this particular application the initial strength gain is the most crucial. Twenty eight day strength is of less importance but is still required to correlate other mechanical properties. The ultimate strength of a product may be an indicator of patch longevity.
- Setting time measurements are needed to indicate the working times for each product.
- Length change is an important property to define a basic component of bonding. If too much shrinkage occurs the bond interface is broken. An important observation is that not all products shrink in air nor do all products expand in water.

- Freeze-thaw testing is one of the most important of all tests for determining the endurance of patching materials. The cold climate of Minnesota imparts a series of freezing and thawing cycles on patches and pavements every year.
- The pull-out bond test provided results indicating that the chemical bond between patching materials and the existing pavement should not be an issue of concern

Recommendations

The four products for consideration to continue on to further test for the project include the following.

- MnDOT 3U18M, TCC
- MnDOT District 3 Mix2, 3U18 based
- Futura-45 Extended, W.R. Meadows
- Rapid Set Concrete Mix, CTS Cement Manufacturing Corp.

The recommendations based on the results of the first round of testing of this research are as follows:

- Flexural strength can be removed from the testing regimen
- Compressive strength measurements can be reduced to only recording the 3 hour and 28 day values
- Shrinkage testing should be required
- Freeze-thaw testing should be required
    - Mass loss should also be reported for the duration of the testing

  - Air entrainment strongly recommended for all patching materials
- Setting times should be recorded and reported

Chapter 4: Testing and Results, Extensive Procedures

Scope of Testing, Products/Materials

The extensive testing portion of the project consisted of six different tests: coefficient of thermal expansion, modulus of elasticity, scaling resistance to deicing chemicals, length change in sulfate solution, abrasion resistance and pop-out bond strength. The only deviation from that standard is the bond strength test, which is described herein.

The four materials that were chosen to undergo the testing during this portion of the project included:

1. MnDOT 3U18M, TCC
2. MnDOT District 3 Mix 2, 3U18 based
3. Futura-45 Extended, W.R. Meadows
4. Rapid Set Concrete Mix, CTS Cement Manufacturing Corp.

These products were chosen in conjunction with the technical advisory panel of the project after a review of the data and recommendations from earlier results.

Testing Procedures and Methodology

The new tests conformed to the recommendations contained within the ASTM C928 standard specification for testing rapid set materials. The tests and their corresponding ASTM designations are located in Table 13.

Table 13: Tests to be conducted on the 4 remaining patch mixes.

Property	Preliminary Test Method
Coefficient of Thermal Expansion	ASTM C531 – Linear Shrinkage and Coefficient of Thermal Expansion of Chemical-Resistant Mortars, Grouts, Monolithic Surfaces, and Polymer Concretes
Modulus of Elasticity	ASTM C469 – Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression
Scaling Resistance	ASTM C672 – Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals
Length Change in Sulfate	ASTM C1012 – Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution
Abrasion Resistance	ASTM C418 – Abrasion Resistance of Concrete by Sandblasting
Pop-out Bond Test	Proposed by Dr. Eric Musselman to simulate slab warping

Coefficient of Thermal Expansion

Coefficient of thermal expansion (CoTE) is a mechanical property that determines the expansion and contraction of a material that is subjected to thermal variations. The units for the CoTE are length per length per degree of temperature change. What this means is that the longer or wider a patch is the more important it is for this property to match the existing pavement. While this is a linear property, it is linear in all directions. For example, a sphere of material would have a change in volume but remain a sphere whether it was shrinking or expanding due to temperature change.

The ASTM C531 specification was used to measure the CoTE. The test involves casting samples in 1 X 1 X 11 inch prism molds (Figure 42), and then measuring the samples at 73°F. Once that is done the samples are heated to 210°F and another length measurement is recorded. The difference in the two measured lengths at a given temperature variation leads to the calculation of the CoTE (k). The CoTE (k) can then be used in the formula for thermal deformation, $\Delta D = L_0 * k * \Delta T$(°F/°C).

- ΔD is the calculated change in length
- L_0 is the initial length of the specimen
- k is the CoTE
- ΔT is the change in temperature

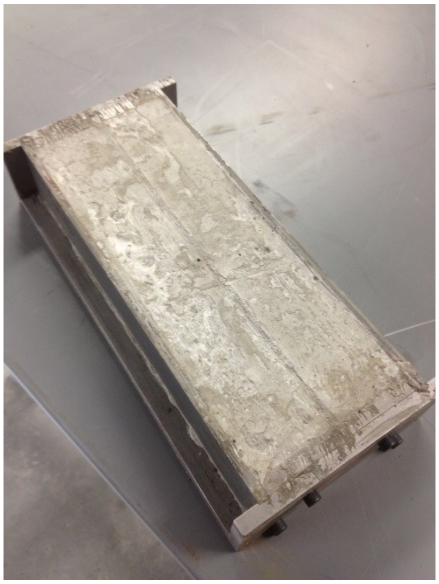


Figure 42: CoTE molded specimens

Considering that this study is focused on cold climate regions it may seem logical that this test be conducted at the temperature extremes that the materials will be subjected to in the field, approximately -30°F to 120°F. However the presence of water in the material would cause the CoTE (*k*) to differ. The water would expand once the temperature fell below freezing, resulting in an erroneous measurement.

The CoTE of the patching mix should be extremely close to that of the concrete slab being repaired. When the two move as one, the bond interface between them stays in contact for a longer duration.

Modulus of Elasticity

The ASTM C469 covers the modulus of elasticity (*E*) and Poisson's ratio. For the purposes of this study only the modulus of elasticity was determined. Modulus of elasticity measures a material's stiffness by comparing the stress over a body versus the strain on that body.

The quantity is a measure of the stiffness only while a material is within the elastic region, before any permanent deformation occurs. Units are typically given in kips per square inch (ksi), a kip is equivalent to one thousand pounds. The units for strain are length/length and therefor cancel out of the modulus ratio.

The apparatus for determining the modulus of elasticity is used in a compression frame and measures deflection of a cylinder (Figure 43).

Figure 43: Modulus of Elasticity apparatus with dial gage

Scaling Resistance to Deicing Chemicals

Due to the colder climate, highways in Minnesota are exposed to large quantities of deicing chemicals each year. The ASTM C672 test procedure was chosen for this reason to evaluate the effects of deicing chemicals on the patching mixes. This test submerges the surface of the specimen in a solution of calcium chloride and water. At prescribed times the surface is visually rated on a scale from 0 to 5.

- Zero – No scaling
- 1 – Very slight scaling, no coarse aggregate visible
- 2 – Slight to moderate scaling
- 3 – Moderate scaling, some coarse aggregate visible
- 4 – Moderate to severe scaling
- 5 – Severe scaling, coarse aggregate visible over the entire surface

The specimen is subjected to a freezing cycle for 16-18 hours followed by a 6-8 hour thawing period, once every 5 cycles each specimen is washed and rinsed to be visually rated before undergoing more cycles. The entire test lasts for a total of 50 cycles. Specimens are cast at a depth of 3 inches and must have the ability to contain the deicing solution on their surface (Figure 44). The white edge is the silicone that was used to seal the perimeter of the specimen.

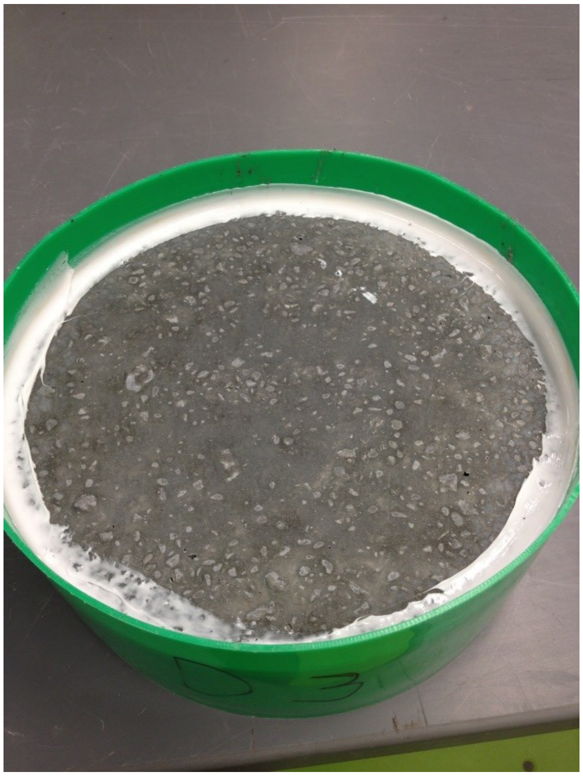


Figure 44: Scaling resistance to deicing chemicals specimen

Length Change in Sulfate

The ASTM C1012 specification measures the length change of a 2 X 2 X 11inch prism shaped specimen (Figure 45). This assesses the products resistance to a sulfate solution; the solution contains 50 grams of sodium sulfate (Na_2SO_4) per liter of water. Specimens are stored in an airtight container filled with the solution and measured at prescribed time intervals.

Figure 45: Length change in sulfate specimen mold

Abrasion Resistance

The abrasion resistance testing follows the ASTM C418 specification. The specification calls for a sandblaster to be used on a concrete specimen at a distance of 3 inches for the duration of one minute. The concave hole that is created is to be filled with clay such that the clay is level with the original surface. The pressure used to insert the clay is prescribed as moderate by the specification. The stockpile of clay is weighed prior to insertion and then weighed again to determine the amount of clay to fill the void. The abrasion coefficient, A_c, is calculated by dividing the volume of the void by the area that was abraded.

Abrasion resistance is an important property to consider when choosing patching materials for use in colder climates. The pavements in colder regions have to cope with not only everyday traffic abrasion but also with the direct contact of steel from snow plows.

The specimens used for this test were 4 inch cylinders 4 inches in length (Figure 46).

Figure 46: Abrasion resistance specimen

Pop-out Bond Test in Flexure

This is the only test that is not an ASTM specification. Eric Musselman proposed this test to simulate the bond strength of the patching materials when the slab is undergoing warping and curling due to climatic and traffic loading factors. Similar specimens were tested performed by Cervo and Schokker (2008).

A representative slab, of a standard MnDOT pavement mix, was cast at a size of 24 X 48 X 7 ½ inches thick. The slab contains steel reinforcement in the corners so that the slab can be flexed beyond the point at which the concrete begins to crack.

A pavement grooving machine was then used to create a typical void in the slab representing a partial depth repair region. This void was then filled with the patching materials. Once cured the slab was subjected to flexure until the bond between the slab and the patching material was broken. The load was recorded for each product and this data was used merely as a comparison of the four products. A photo of the test slabs is in Figure 47.

Figure 47: Test slabs for the pop-out bond test

The flexural pop-out bond test setup utilized a hydraulic ram and load cell. The load was recorded throughout the test. A schematic of the slab indicating the support points as well as the load point is in Figure 48.

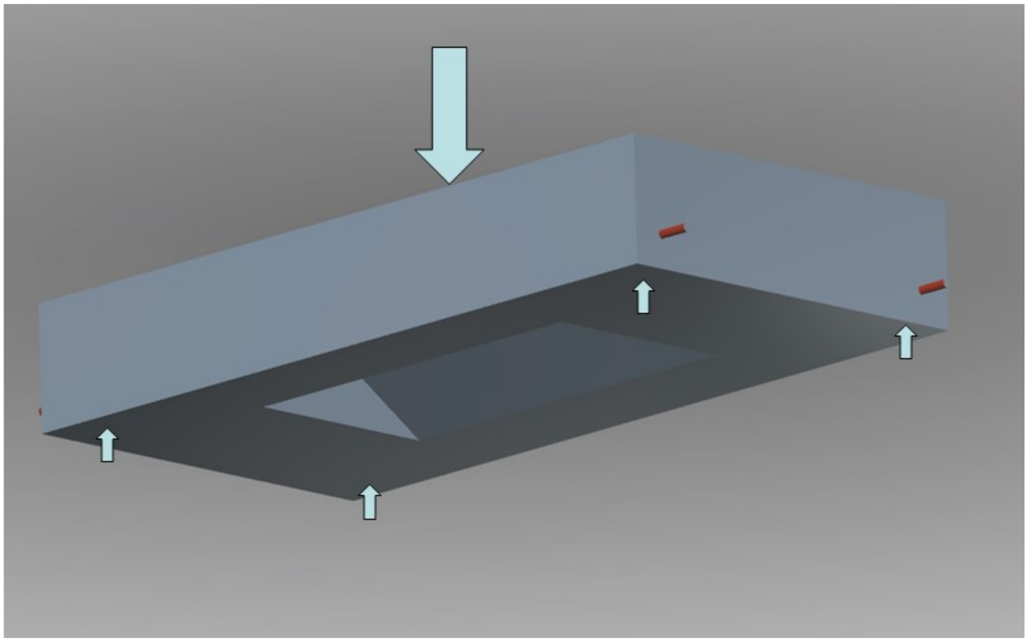


Figure 48: Schematic of the pop-out bond test

Laboratory Mixing and Specimen Preparation

There was a modification to the Futura 45 product that was used earlier in the study. For this round of testing Futura 45 was used because it is the product most likely to be used in the field. This mix does not contain any aggregate; this means it must be extended with a local source. MnDOT gradation CA-80 was used to extend the Futura 45 (MnDOT 3137). The setting time and 28 day compressive strength were measured for this version of Futura 45 (Table 14).

Table 14: Futura 45 EXT and Futura 45 data.

	Futura 45 EXT (initial testing)	Futura 45
Initial Set Time (min)	47	53
Final Set Time (min)	72	80
Compressive Strength (psi)	8509	7790

Testing Results

Coefficient of Thermal Expansion (CoTE)

The CoTE was measured on two separate samples of normal concrete for comparison purposes. One of those controls contained limestone based aggregate from the southern region of Minnesota and the other contained granite based aggregate. The results of the test show that the materials are moderately close to one another (Figure 49). A box and whisker plot is presented in Figure 59 of Appendix-B which shows the variability of the measurements that were taken of the four replicate samples.

The two purely PCC based products, 3U18M and District 3 Mix 2, are nearly the same as the normal PCC samples.

The Futura 45 has the lowest CoTE of the group that was tested. This could be a detrimental factor for patches of large size, this being due to the fact that CoTE is on a scale of length change per length for each degree of temperature change.

Rapid Set had the largest CoTE at 1.05E -5 mm/mm/ °C.

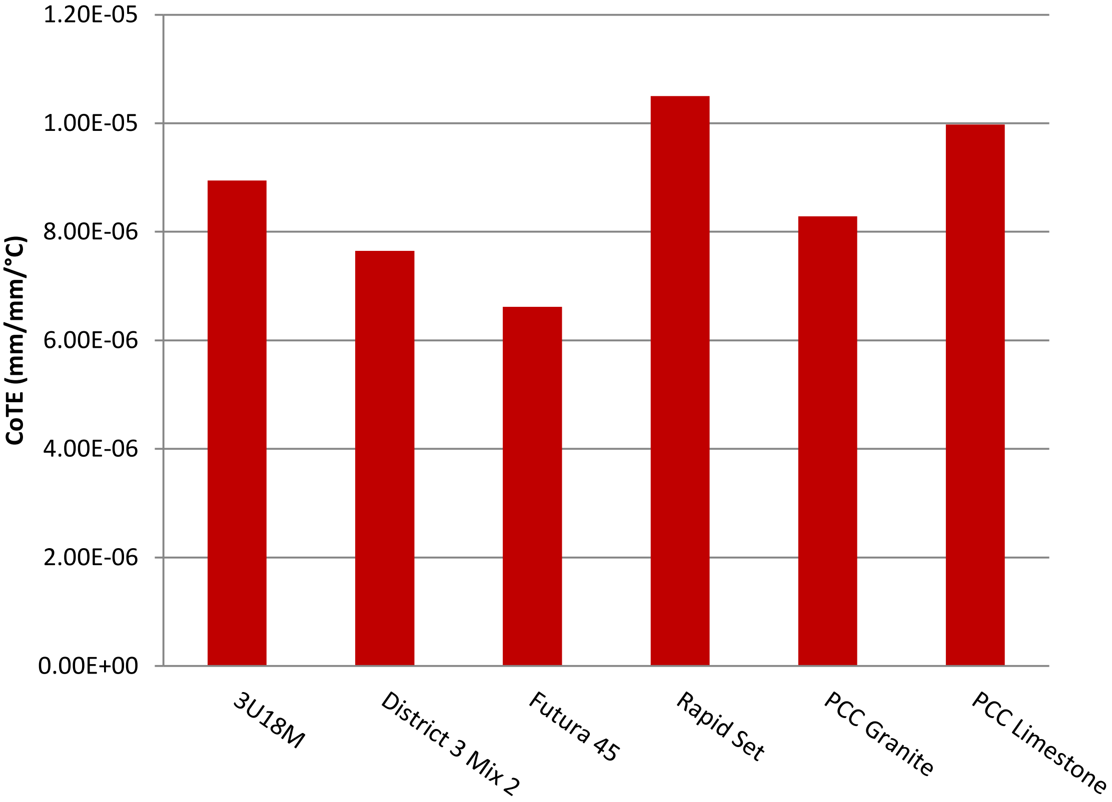


Figure 49: Coefficient of Thermal Expansion

Modulus of Elasticity

The two control mixes of PCC mentioned in the CoTE were also used for this test. Both of the control mixes exhibited values that are typical of normal concrete. Unexpectedly the granite based aggregate concrete had a lower stiffness than the softer limestone based aggregate. This is most likely due to the size of the aggregates used; the crushed limestone was considerably larger than the crushed granite.

The 3U18M elastic modulus value is similar to normal concrete; a comparable trend was realized in the results for the District 3 mix. This is expected because both of them are Portland cement based products. However this is also unexpected because typically the elastic modulus increases as compressive strength increases, both the 3U18M and the District 3 mix have more than double the amount of compressive strength of normal concrete. A reason for this may be the size of the aggregate used in these two patching mixes, larger aggregate typically results in a higher elastic modulus and these products contain aggregate that does not exceed 3/8 of an inch whereas the normal concrete samples contained aggregate sizes exceeding one inch.

The elastic modulus of Futura 45 falls between the elastic modulus values of the PCC granite and the PCC limestone, both are representative of a typical pavement mix concrete. This data suggests that the Futura 45 matches the stiffness of normal pavement concrete.

Rapid Set has the lowest elastic modulus of any of the materials tested during this portion of the research. The results show that Rapid Set has only slightly more than half the modulus of the other products (Figure 50). The variation among the replicate samples is presented by way of a box and whisker plot (Figure 58 Appendix-B).

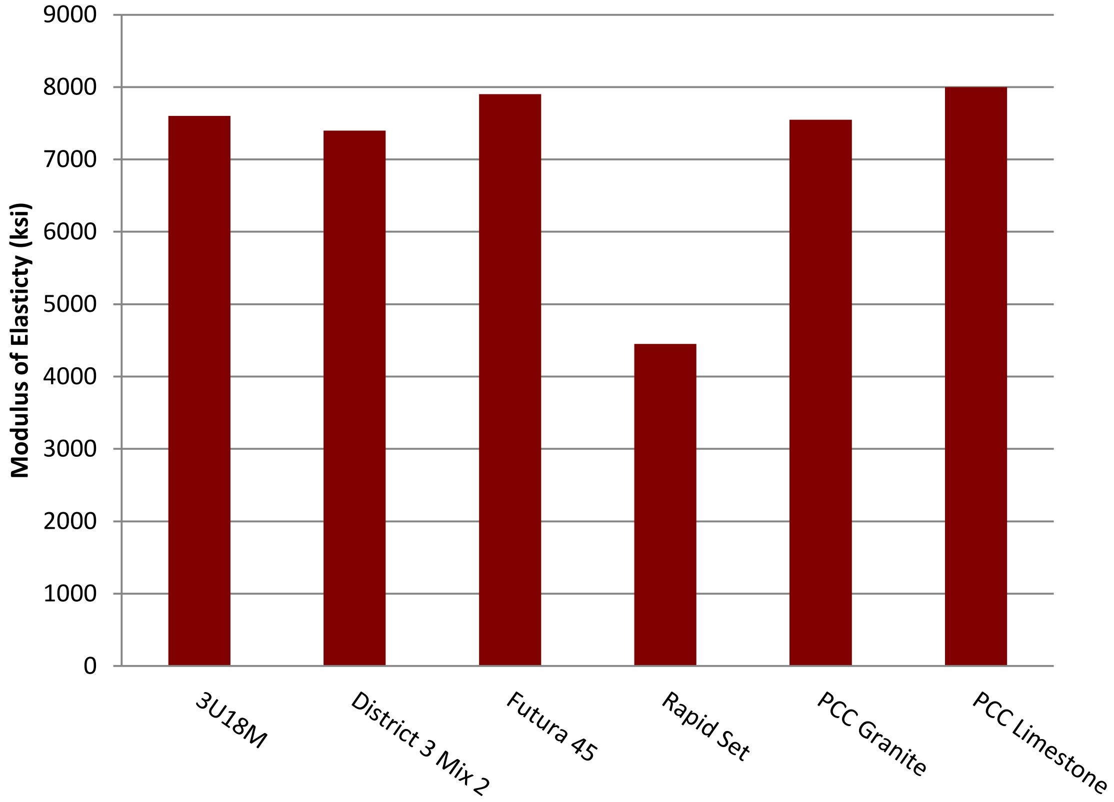


Figure 50: Modulus of Elasticity Results

A comparison was also made between the elastic modulus findings and the dynamic modulus results from the freeze thaw tests performed earlier. There is no apparent correlation between the two different test results (Figure 51). The line in the plot below shows no linear trend. This was performed with a very limited group of specimens and should be investigated further.

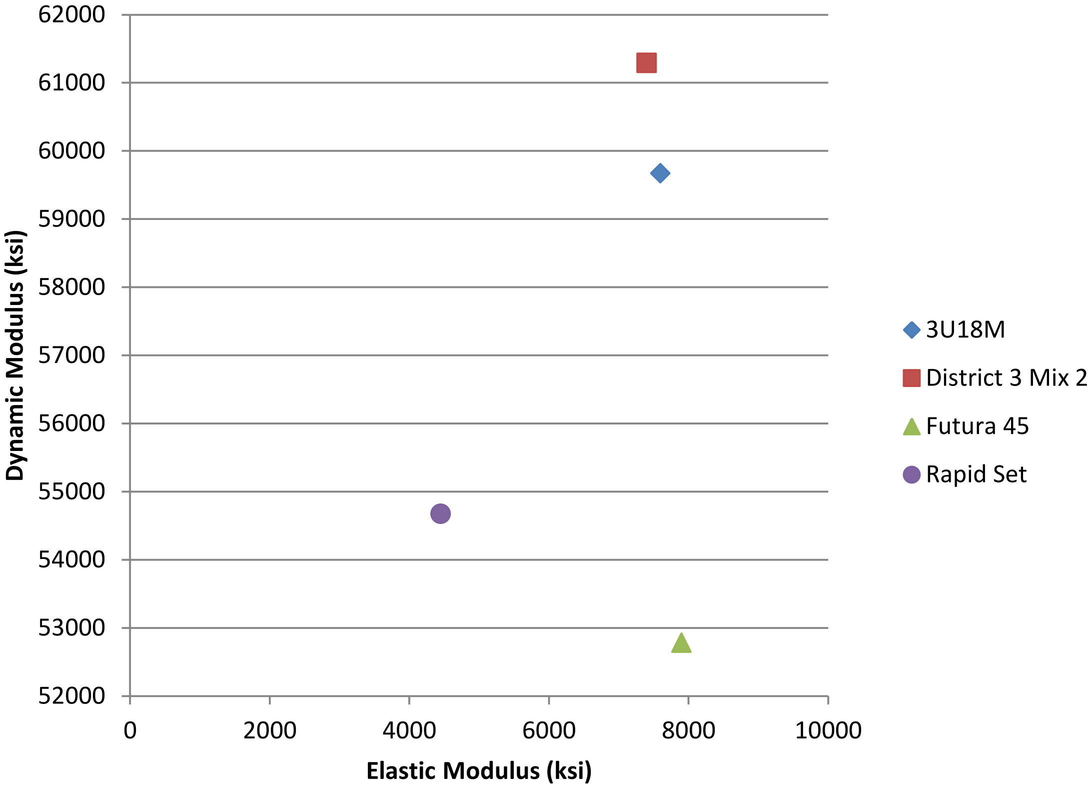


Figure 51: Dynamic Modulus vs. Modulus of Elasticity

Another comparison of mechanical properties was performed to check for correlations. Modulus of elasticity was plotted against CoTE (Figure 52). The plot shows that there is a reverse correlation between the stiffness of a material and the rate at which it expands and contracts with temperature. Rapid Set had the lowest modulus of elasticity but showed the largest CoTE.

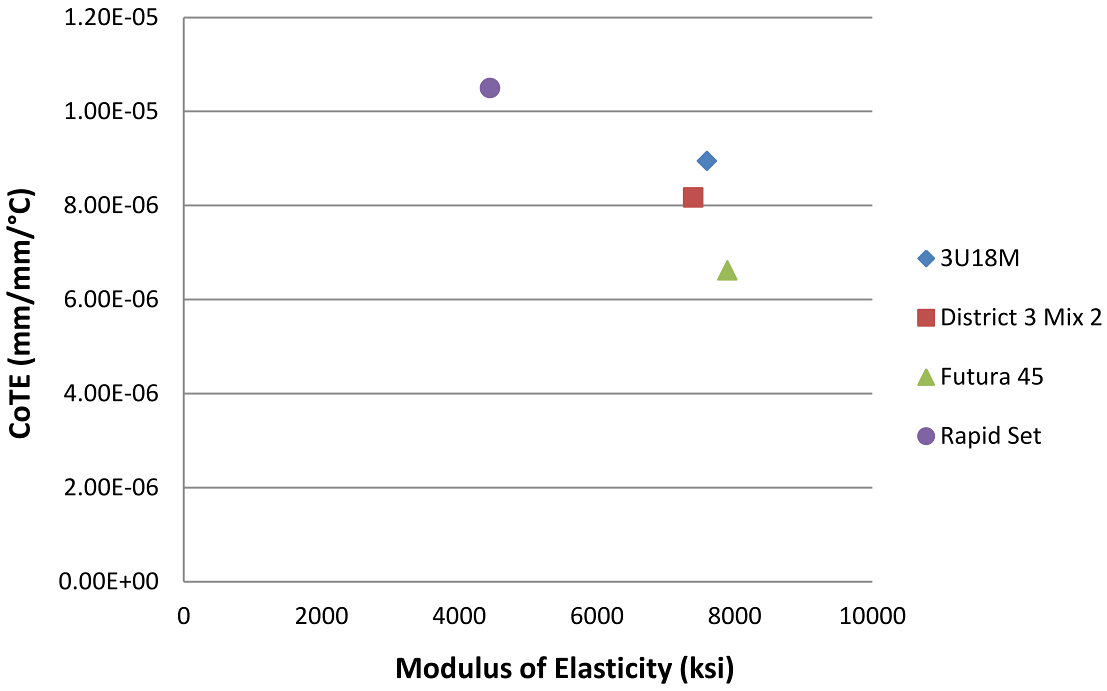


Figure 52: CoTE vs. Modulus of Elasticity

Scaling Resistance to Deicing Chemicals

Results of the sulfate resistance to deicing chemicals will be available upon completion of the test.

Length Change in Sulfate

The results of this test will be available upon completion once the test is complete.

Abrasion Resistance

The abrasion coefficient is an empirical measurement used to rate a material's aversion to being worn due to direct physical contact. A lower abrasion coefficient indicates more resistance to abrasion.

The results show that the PCC with limestone aggregate abraded more readily than the PCC with granite aggregate. This was expected because some of the abraded area contains aggregate and the limestone is less stiff than granite.

The rapid set materials did show variability amongst the group (Figure 53). 3U18M, District 3 Mix 2 and Futura 45 had abrasion coefficients that are within ten percent of one another. The Rapid Set was above the rest of the group, sixty percent higher than the closest patching material.

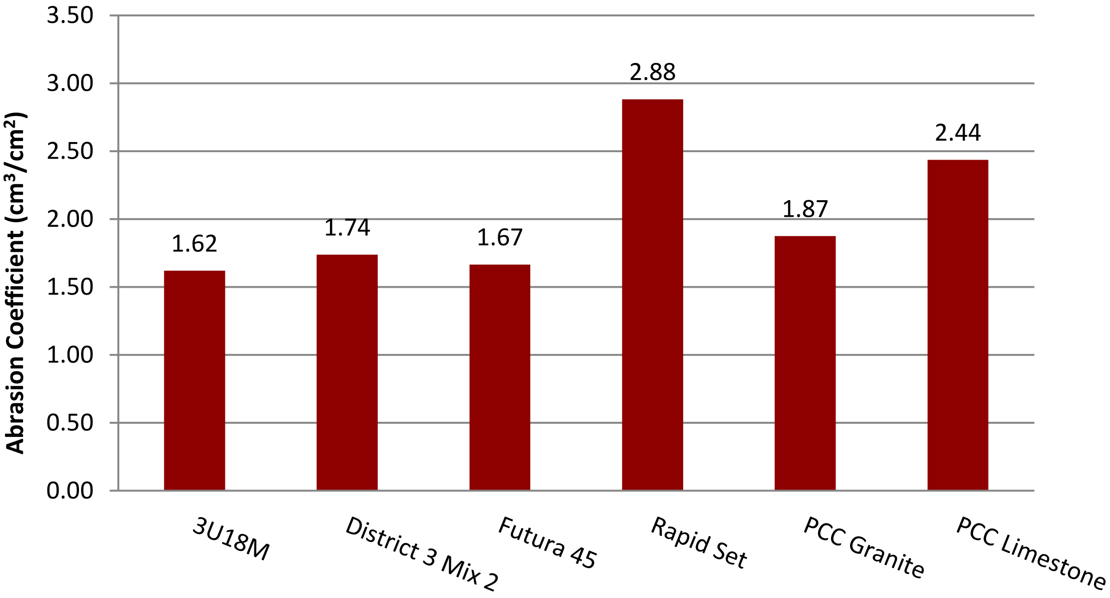


Figure 53: Abrasion Coefficient results

When comparing the abrasion coefficient with the modulus of elasticity there is a correlation between how stiff a material is and how well it resists abrading. The data in Figure 54 shows that Rapid Set which had the lowest modulus of elasticity also displayed the highest abrasion coefficient. The outlier in the plot is the PCC with limestone aggregate, the softer aggregate actually abraded along with the PCC paste, this resulted in a larger volume of material being removed.

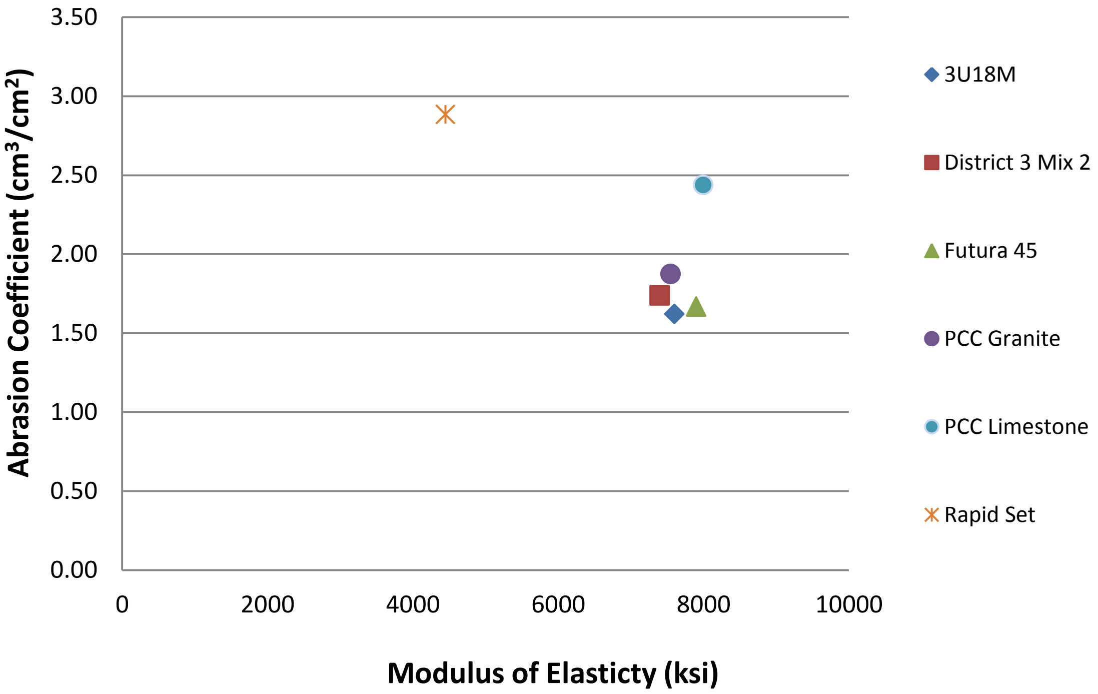


Figure 54: Abrasion Coefficient vs. Modulus of Elasticity

The specimens are shown after the test was conducted in Figure 55. The specimen marked PCCS has the limestone aggregate, note how smooth the abraded area is. The opposite can be seen on the PCCL sample, the aggregate in the abraded area is intact.

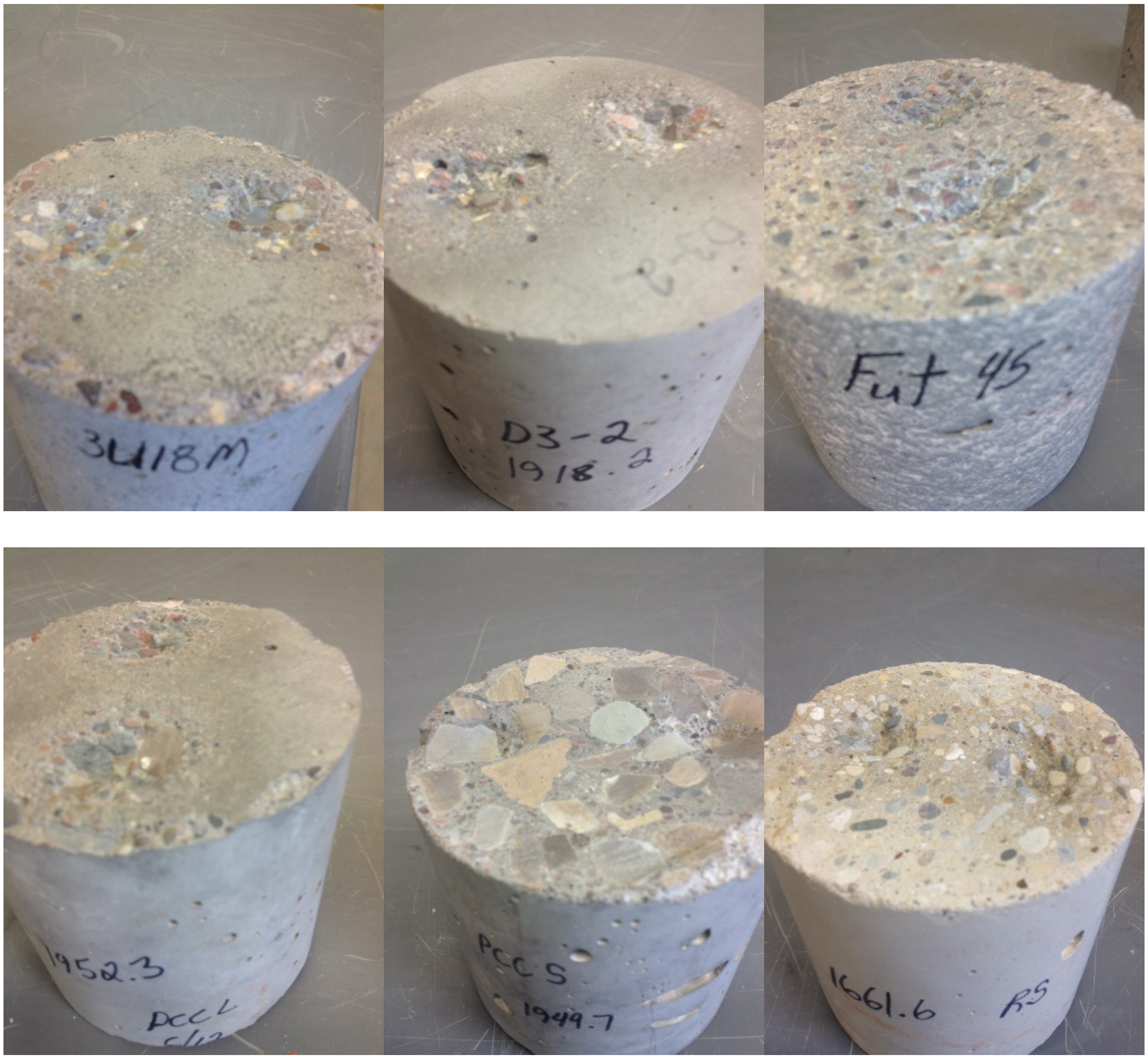


Figure 55: Abrasion test specimens

Pop-out Bond Test in Flexure

The results of this test will be available upon completion once the test is complete.

Summary

The more extensive tests were chosen because the properties measured are of more importance when considering a colder climate. A number of correlations were observed, not only among the tests involved during this portion of testing but also with previous tests. The results of these correlations present more options to consider for the acceptance of rapid set cementitious materials.

- CoTE is an important property to consider
    - The correlation with the modulus of elasticity may be used to screen the materials that would require CoTE testing versus those that may have properties compatible to typical pavement PCC.
    - Further research is required to establish an acceptable range that the CoTE should adhere to for acceptance as a patching material.
- Modulus of Elasticity measures the stiffness of a material and should closely match the existing pavement
- In colder climates abrasion resistance is essential because of the added abrading from snow plows
    - The results from four mixes show that there is a relationship between abrasion resistance and the modulus of elasticity

Recommendations

While each of the properties measured in this phase are important to partial depth patching on cold climate regions some may be obtained indirectly. Consideration must be given to each test and to what condition in the field each of them represent. The data collected was gathered from a small test group and the following is based on that data. Future studies on additional materials would provide further confirmation and they are strongly recommended.

- Modulus of elasticity of patch material should be measured and compared to the modulus of elasticity of PCC used for pavement construction.
- Coefficient of Thermal Expansion can be eliminated from testing when considering PCC based products.
    - The correlation with stiffness is sufficient in determining the validity of a PCC based material for a thermal property match.
    - There weren’t enough products represented in this testing to eliminate this test completely for other materials that are not PCC based.
- Abrasion resistance should be performed on products containing softer aggregates that may be susceptible to polishing.

Chapter 6: Summary, Conclusions and Recommendations

Summary

The project was originally proposed because of the need for better patching materials. The best way to control the quality of the patching materials is to develop a set of criteria that ensures that only the best products are being used in the field.

This study started with thirteen products that were representative of typical products that are used for patching Portland cement concrete pavements in Minnesota. The testing of these products followed the required ASTM C928 specification for rapid setting cementitious materials and an adapted ASTM C900 bond strength test.

Those tests included:

- Compressive strength gain
- Flexural strength at 4 hours
- Setting time
- Freeze thaw durability
- Length change in air and water
- Bond strength (pull-out)

Once the data had been collected and analyzed a determination of the final four products was made. The four products that were chosen then went on to a more rigorous testing regimen. The premise of this portion of the study is to develop a criterion that not only follows recommendations made by the ASTM C928 specification but also to develop new tests for future consideration.

The tests for the final part of the study included:

- Coefficient of thermal expansion
- Modulus of elasticity
- Scaling resistance to deicing chemicals
- Length change in sulfate solution
- Abrasion resistance
- Pop-out bond test in flexure

When analyzing the data from these tests a few correlations were found among the results. This could lead to some tests being removed or limiting their use in the future.

Conclusions

The current ASTM C928 specification regarding the acceptance criteria for rapid set cementitious materials contains five requirements as well as four recommended tests of physical and mechanical properties. This study performed three of the required tests and all of the recommended tests in the ASTM specification. Other tests were proposed and performed during this research project. A complete list of tests and specifications are listed in Table 15.

Table 15: Tests performed during this study

Property	ASTM designation/ test description
Set time	ASTM C191 – Standard Test Method for Time of Setting of Hydraulic Cement by Vicat Needle
Strength gain	Time interval testing (3 hours, 24 hours, 7 days and 28 days) using ASTM C 39 – Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens
Flexural strength	ASTM C78 – Standard Test Method for Flexural Strength of Concrete (at 4 hours)
Shrinkage	ASTM C490 - Standard Practice for Use of Apparatus for the Determination of Length Change of Hardened Cement Paste, Mortar, and Concrete
Bond strength	Modified version of ASTM C900 – Standard Test Method for Pullout Strength of Hardened Concrete
Freeze-thaw durability	ASTM C666 - Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing
Coefficient of Thermal Expansion	ASTM C531 – Linear Shrinkage and Coefficient of Thermal Expansion of Chemical-Resistant Mortars, Grouts, Monolithic Surfaces, and Polymer Concretes
Modulus of Elasticity	ASTM C469 – Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression
Scaling Resistance	ASTM C672 – Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals
Length Change in Sulfate	ASTM C1012 – Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution
Abrasion Resistance	ASTM C418 – Abrasion Resistance of Concrete by Sandblasting
Pop-out Bond Test	Proposed by Dr. Eric Musselman to simulate slab curling

One of the tests required by the ASTM C928 was not performed during this study as it was deemed inconsequential to the acceptance of rapid set materials. The slant shear bond strength test was excluded. Consistency of mortar testing was conducted, however for the purpose of this study the materials were compared to the ASTM C928 specification. The reason for this was that materials that MnDOT used prior to and during this study have slump values that are below the current requirements. The slump data is located in Appendix-B Phase 1.

The recommended specifications included two tests that were deemed to be necessary for the acceptance of patching materials, particularly for colder climates. The setting time of materials was judged to be essential for indicating lane closure times.

Freeze thaw testing proved to be of utmost significance. This one test provides a plethora of information about a material's ability to withstand the rigors of colder climates. Other data to be collected during the freeze thaw test include: initial dynamic modulus and mass loss throughout the entire testing procedure. While the mass loss is not an indicator of the material's freeze thaw durability in terms of its mechanical integrity, it can provide insight to the retention of installed patch and its surface performance over the time.

Properties such as the coefficient of thermal expansion are important; it should match as closely to the existing pavement as possible. However the preliminary results of the four products indicated that CoTE may be derived from the modulus of elasticity; this is the case for PCC based products only, non-PCC based products should be tested. Without further research it is uncertain how closely this property must be to the existing pavement to be considered a match.

There are many contributing factors to patch failure. This study was performed for the purpose of accepting only the most qualified materials for partial depth patching in cold climates. The tests that are recommended herein will help to determine which materials are suitable for patching and which materials do not possess the appropriate attributes for use in partial depth repair.

Recommendations

The data indicates that the following tests and procedures should be considered when evaluating new and current products for the use of partial depth repair in PCC pavements.

- Flexural strength can be removed from the testing regimen
- Compressive strength measurements can be reduced to only recording the 3 hour and 28 day values
- Shrinkage testing is recommended
- Freeze-thaw testing should be required
    - Mass loss should also be reported for the duration of the testing
    - Air entrainment strongly recommended for all patching materials
    - The initial dynamic modulus should be recorded
- Setting times should be recorded and reported
- The pull-out bond test proposed for this study showed that the chemical bond of these materials is of little concern
    - This test is not recommended as an add-on to the ASTM C928 specification
- Modulus of elasticity should be measured and compared to typical modulus value for highway PCC slabs
    - The two values should match closely, an exact range of acceptable percentages needs to be determined

- Coefficient of thermal expansion should be measured and compared to PCC coefficient of thermal expansion
    - The correlation with elastic modulus is sufficient in determining coefficient of thermal expansion in PCC based products
- Abrasion resistance should be performed on products containing aggregates that may be suspect due to their potential for polishing under traffic load and also due to the action of snow plows

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Appendix-A: Typical Partial Depth Repair Schematics

There are two types of partial depth repair that are common. The first is a failure that involves only one side of a joint in the pavement (Figure 56). This repair requires special care not to disturb the pavement on the side of the joint that is not affected by spalling. The second type of failure that requires repair is when both sides of a joint are spalled (Figure 57). For the double sided repair the grinder can simply follow the spalled area until all necessary material has been removed. Both of these repairs require that the existing joint be maintained through the use of a bond breaker.

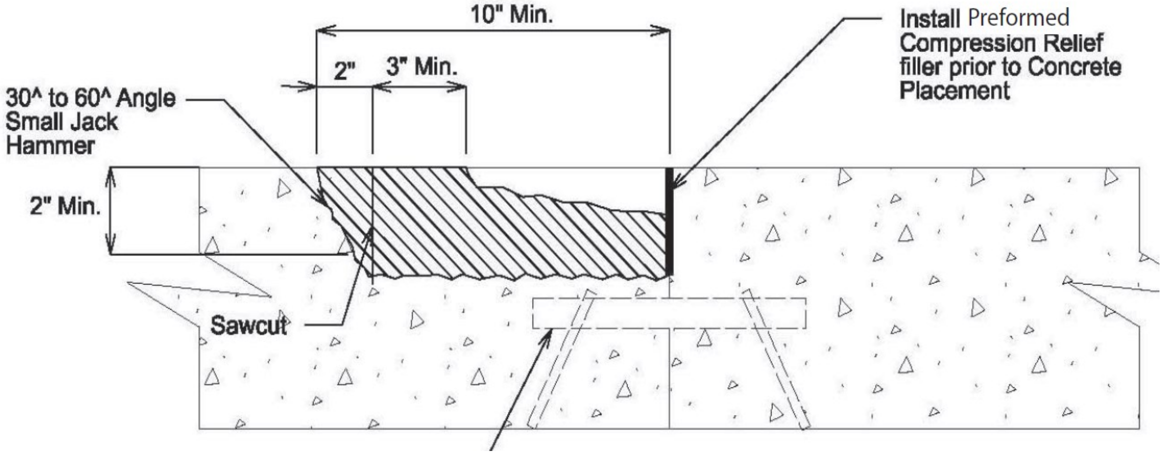

Figure 56: Single side partial depth repair schematic

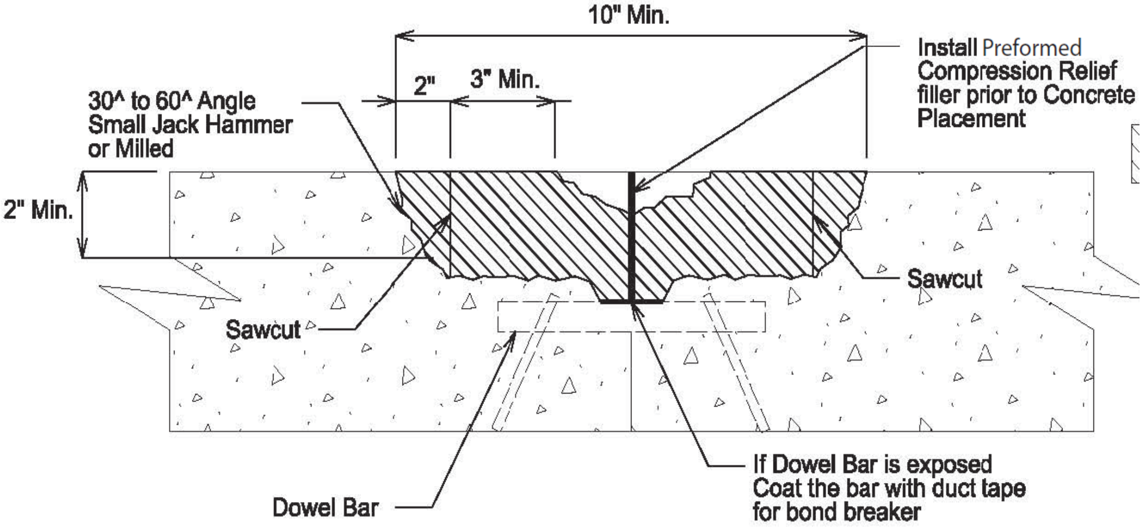

Figure 57: Two sided partial depth repair schematic

Appendix-B: Raw Data

Phase 1

Product	3 Hour Comp (psi)
Five star	4527
Futura 45	4333
Futura 15	4179
Rapid Set Concrete Mix	3965
Pavemend SL	3929
Pavemend SLQ	2402
Mono Patch	2392
TCC Taconite	1639
Akona	354
District 3 mix 1	0
3U18M	0
District 3 mix 2	0
3U18	0

Product	1 Day Comp (psi)
District 3 mix 2	6608
District 3 mix 1	6388
Pavemend SL	5811
Futura 45	5650
Five star	5299
Futura 15	5127
Mono Patch	4568
Rapid Set Concrete Mix	4526
3U18	4233
3U18M	3886
Pavemend SLQ	3725
TCC Taconite	2765
Akona	1720

Product	7 Day Comp (psi)
District 3 mix 2	9571
District 3 mix 1	9038
Futura 15	8083
Futura 45	7449
Pavemend SL	7437
3U18M	7327
3U18	7162
Five star	5835
Rapid Set Concrete Mix	5638
Mono Patch	5555
Pavemend SLQ	4285
Akona	3946
TCC Taconite	3020

Product	28 Day Comp (psi)
District 3 mix 2	11236
District 3 mix 1	9677
Pavemend SL	9172
Futura 15	8838
3U18M	8610
Futura 45	8509
3U18	8463
Mono Patch	8126
Five star	6518
Rapid Set Concrete Mix	6488
Akona	5454
Pavemend SLQ	4985
TCC Taconite	1852

Product	Modulus of Rupture - 4 hour flex (psi)
3U18	13
3U18M	2
Akona	160
District 3 mix 1	268
District 3 mix 2	175
Five star	606
Futura 15	606
Futura 45	466
Mono Patch	417
Pavemend SL	592
Pavemend SLQ	418
Rapid Set Concrete Mix	426
TCC Taconite Mix	306

Product	Length Change (%)	
	Air	Water
Rapid Set Concrete Mix	-0.04	0.032
Pavemend SLQ	0.018	0.026
Pavemend SL	-0.034	0.024
Mono Patch	0.006	0.364
Futura 45	-0.049	0.02
Futura 15	-0.08	0.002
Five star	-0.034	0.021
District 3 mix 2	-0.084	0.017
District 3 mix 1	-0.08	0.053
Akona	-0.025	0.07
3U18M	-0.085	0.021
3U18	-0.055	0.024
TCC Taconite	Un-measurable	-0.03

Product	Durability Factor DF
3U18	14.4
3U18M	23.59
Akona	2.87
District 3 mix 2	28.44
District3 mix 1	17.5
Five Star	4.57
Futura 15	17.9
Futura 45	100.17
Monopatch	96.23
Pavemend SL	16.78
Pavemend SLQ	117.23
Rapid Set Concrete Mix	18.2
TCC Taconite	121.66
Normal Concrete	95

Product	Set time (min)	
	initial	Final
3U18	174	230
3U18M	183	210
Akona	75	150
District 3 mix 2	180	230
District3 mix 1	180	230
Five star	11	12
Futura 15	25	34
Futura 45	47	72
Monopatch	33	44
Pavemend SL	11	20
Pavemend SLQ	4	6
Rapid Set Concrete Mix	18	27
TCC Taconite Mix	24	32

Product	Slump (inches)
3U18	0.75
3U18M	2
Akona	Self-leveling
District 3 Mix 1	7.5
District 3 Mix 2	2.5
Five Star	Self-leveling
Futura 15	Self-leveling
Futura 45	9
Mono Patch	7.75
Pavemend SL	Self-leveling
Pavemend SLQ	Self-leveling
Rapid Set	Self-leveling
TCC Taconite Mix	Not Available

Concrete for the pop out test					Avg.
	1	2	3	4	
Load (lbs.)	62970	74300	78930	76180	
Area (in^2)	12.566	12.566	12.566	12.566	
28 day comp (psi)	5011.00	5912.61	6281.06	6062.22	5816.7
Failure Type	5	5	5	5	
Air content (%)	5.30				
Slump (in.)	2.375				

Phase 2

CoTE	mm/mm/°C
3U18M	8.95E-06
District 3 Mix 2	7.65E-06
Futura 45	6.62E-06
Rapid Set	1.05E-05
PCC Granite	8.28E-06
PCC Limestone	9.97E-06

Elastic Modulus Values	(ksi)
3U18M	7600
District 3 Mix 2	7400
Futura 45	7900
Rapid Set	4450
PCC Granite	7550
PCC Limestone	8000

Abrasion Resistance test	Abraded Volume (cm^3)	Abraded Area (cm^2)	Abrasion Coefficient
3U18M	10.45	6.45	1.62
District 3 Mix 2	11.21	6.45	1.74
Futura 45	10.75	6.45	1.67
Rapid Set	18.60	6.45	2.88
PCC Granite	12.09	6.45	1.87
PCC Limestone	15.72	6.45	2.44

Box Plots for Elastic Modulus and CoTE

The variability amongst the four replicate samples for both the elastic modulus and the coefficient of thermal expansion are displayed in the following box and whisker plots (Figure 58 and Figure 59). The minimum and maximum values that were recorded are indicated by the error bars in the plots. Subsequent measurements are represented by the top and bottom of the boxes while the average value of the four replicates lies where the green box meets the red box.

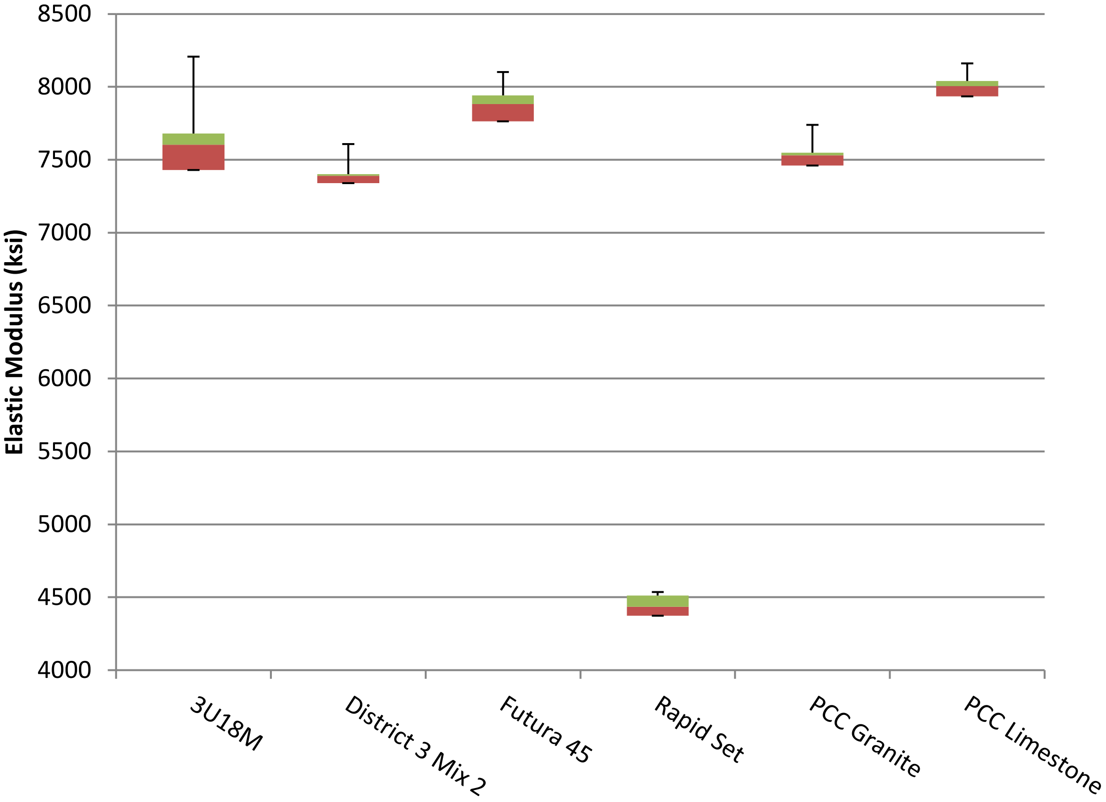

Figure 58: Box and whisker plot for the elastic modulus

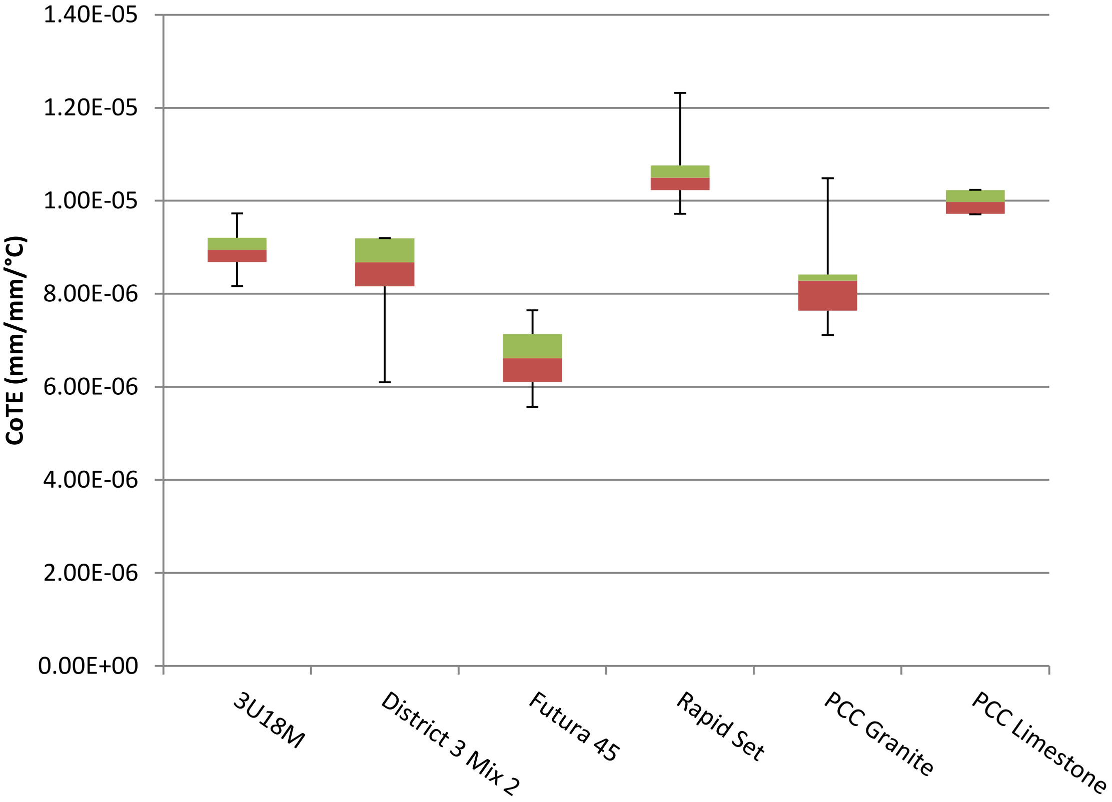

Figure 59: Box and whisker plot for coefficient of thermal expansion

Appendix-C: Best Practices

Methods

There are different approaches to installing partial depth patches in PCC pavements. The way that a patch area is prepared is critical to the success of any patch. There are two widely accepted methods for preparing the area to be patched. The first is the saw cut and removal method; this creates a vertical edge at the border of the patch (Figure 60). The second is the grinding and chipping procedure which utilizes a light weight jack hammer to taper the edges of the patch area; the taper angle can vary from 30 to 60 degrees (Figure 61).

Figure 60: Saw-cut edge of a patch area, vertical face

Figure 61: Tapered edges of two opposing corner partial depth repairs

The saw-cut method results in a smooth face for the patching material to bond with. The result is that the only bond available is a chemical bond between the patch and the substrate. Without the presence of any mechanical bond, aggregate interlock, the chemical bond alone is susceptible to any shrinkage that may occur (Figure 62).

Figure 62: Edge de-bonding due to shrinkage along a saw-cut patch area

The grinding and chipping method leaves a rough surface for the patching material to adhere with. This provides the patch material a greater surface area and develops a continuous mechanical bond at the patch/substrate interface. Once the edges have been prepared the patch area must be thoroughly cleaned so that no loose material or dust remains, compressed air is often used for this purpose.

After the patch area has been prepared it is ready to have patching material placed. A common approach to increase the bond that is developed is to place a thin layer of cement slurry to the patch surface. The patching material must be placed onto the slurry while it is still wet.

Another component of patching is to maintain all existing joints that are in the pavement. There are two materials commonly used for the purpose of preserving working joints in pavements. The first is a wax covered cardboard which is quite stiff and retains its shape during the placement of patching material. The wax provides a moisture barrier so that the patching material cannot leach through to eliminate the joint. The second is a manufactured fiber board that can be cut to size easily and also retains its shape (Figure 74). A measure that can be employed after the material has set is to saw-cut a new joint where the previous joint was located. This method is less than ideal but can be used if a joint was missed or if the joint maintaining materials fail.

Rapid set cementitious materials, as the name suggests, set up quickly. The finishing and curing of the filled patch is also of importance for the success of partial depth patches. Two common types of curing procedures include the use of a curing compound or wetting the surface with water and covering with plastic. A finished patch with a commercial curing compound can be seen in Figure 73. Curing with water and plastic can yield good results (Figure 63). Patches that receive no curing method of any kind, simply exposed to the air, tend to dry out rapidly and experience surface shrinkage cracking (Figure 64).

Figure 63: Wetted and covered curing method result

Figure 64: Cracked patch that was placed with no curing

Minnesota Concrete Patch Repair Process (Field Visit Summary)

A field visit was made in August of 2012 to observe the current practices of partial depth patching in Minnesota. The location was on Cedar Avenue south of the Mall of America in Eagan MN. The following is a comprehensive photo essay explaining the processes of partial depth repair as mandated by the Minnesota Department of Transportation construction specifications (Figure 65 through Figure 74).

Figure 65: Milling machine grinding a spalled section of concrete

Figure 66: Chipping the edges to meet MnDOT specifications

Figure 67: Air blasting the hole to remove excess loose material

Figure 68: Sandblasting the patch area prior to being filled

Figure 69: Truck loaded with the pre-bagged rapid set cementitious material

Figure 70: The mixing operation

Figure 71: Applying the concrete slurry that provides adhesion for the patch material

Figure 72: Placement, consolidation and finishing

Figure 73: Finished patch with curing compound applied

Figure 74: A finished patch with fiber board inserted to maintain a working joint

Summary

There are many different approaches to performing partial depth patching on PCC pavements. When considering the pavements that exist in the colder climate regions of the USA and Canada, greater care must be given not only to the materials that are used, but to the procedures used in placing the patches.

Key points for consideration:

- Patch area preparation
    - Saw-cut edges
    - Tapered edges
- Maintaining the existing joints
    - Use wax covered cardboard

    - Use fiber board
    - Saw-cut a new joint
- Patch material curing process
    - No curing
    - Wetted and covered with a moisture barrier
    - Commercial curing compound

Recommendations

The following is a comprehensive list of the practices and procedures that are currently used by MnDOT.

Procedures to be followed:

- Edge preparation
    - Grinding of the patch area
    - Chip the edges with a lightweight jackhammer (<30 lbs.), maintaining a 30-60 angle of approach
- Patch area cleaning
    - Air blast all loose material from within the patch
    - Sand blast the patch area to remove any remaining loose material
- Place joint maintaining materials
    - Wax covered cardboard
    - Fiber board
- Adhesion slurry

    - Patching material must be placed on the slurry while wet, if the slurry dries it must be reapplied
- Place, consolidate and finish the patch material
- Cure the patch
    - Commercial curing compound, sealer
    - Wet the surface with water and cover with moisture barrier