Field Observation of Installation and Performance of Repair Materials

Larisa Diana Susinskas

FIELD OBSERVATION OF INSTALLATION AND PERFORMANCE OF REPAIR MATERIALS

LARISA D. SUSINSKAS

Bachelor of Science in Civil Engineering

Cleveland State University

May 2015

Submitted in partial fulfillment of requirements for the degree

MASTER OF SCIENCE IN CIVIL ENGINEERING

CLEVELAND STATE UNIVERSITY

AUGUST 2016

We hereby approve the thesis of

Larisa D. Susinskas

Candidate for the Master of Science in Civil Engineering degree

for the department of

Civil Engineering

and the

CLEVELAND STATE UNIVERSITY

College of Graduate Studies by

Signature of Chairperson of the Committee here

Dr. Norbert Delatte

____

____

Department and Date

Signature of Committee Member here

Dr. Jacqueline Jenkins

____

____

Department and Date

Signature of Committee Member here

Dr. Mehdi Jalalpour

____

____

Department and Date

5/11/2016

Student's Date of Defense

ACKNOWLEDGEMENTS

This study was sponsored by the Ohio Department of Transportation (ODOT), under a research contract titled “Evaluation of High Performance Pavement and Bridge Deck Wearing Surface Repair Materials,” State Job Number 134816, Agreement Number 25969. The Civil and Environmental Engineering Department, Washkewicz College of Engineering, and the College of Graduate Studies at Cleveland State University also supported the research.

The objective of this study was successfully accomplished with the assistance of a number of groups and individuals. The research team would like to acknowledge and thank ODOT District 8 for their assistance, support, and coordination to make the field installation and testing possible. Thanks to Ed Pristov and Pile Dynamics for loaning the Acoustic Concrete Tester; without you, this research would have never happened. A special thanks to the University of Cincinnati’s Dr. Richard Miller and Mohammad Asghar for their time and assistance, Cleveland State University graduate student Jennifer Woods and undergraduate student Michelle Seitz for their input and assistance, and Dr. Norbert Delatte for his support and knowledge of the subject.

FIELD OBSERVATION OF INSTALLATION AND

PERFORMANCE OF REPAIR MATERIALS

LARISA D. SUSINSKAS

ABSTRACT

The state of Ohio is in a region that commonly experiences drastic changes in weather. States with similar climates are susceptible to pavement cracking and failures due to the frequent or extreme freeze-thaw cycles. Freeze-thaw cycles, paired with de-icing chemicals that are frequently placed on roadways during the winter months will most likely lead to pavement cracks and failure. Ohio Department of Transportation (ODOT) routinely repairs and replaces sections of concrete roadways and bridge decks. Therefore, ODOT is seeking durable, cost-effective materials to repair smaller pavement failures.

The purpose of this study is to determine which high performance repair materials would be suitable for implementation in ODOT's construction practices. This includes selecting a variety of high performance repair materials, installing said materials in the field, conducting laboratory testing, and determining which materials are the most efficient and cost-effective. The activities that occurred during this study consist of visual inspections of previously installed high performance repair material patches, the nondestructive testing of each patch, and the installation of two types of selected repair materials. These repair materials are MG Krete and RepCon 928. The results of this study will help determine which of these materials would be optimal to implement in areas with extreme climates.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER I

INTRODUCTION AND RESEARCH OBJECTIVES

1.1 Introduction

This thesis covers the field observation of the installation and performance of repair materials for highway pavements and bridge decks. This was done as part of a Cleveland State University research project for the Ohio Department of Transportation. This project focuses on the nondestructive testing procedures and methods conducted on the previously installed repaired patch locations in Xenia, Ohio. Similarly, this thesis follows Alice Sommerville's and Andrew Lesak's theses covering the selection of the high performance repair materials and field-testing of high performance repair materials. (Sommerville, 2014 and Lesak, 2014).

1.2 ODOT Problem Statement

The Ohio Department of Transportation (ODOT) is searching for new means to repair and improve pavement and bridge deck failure areas that occur unexpectedly. Because Ohio encounters frequent freeze-thaw cycles due to the drastic changes in weather patterns between the seasons, pavements are more susceptible to cracking and failure. Thus, ODOT desires pavement repair materials that are durable enough to endure the freeze-thaw cycles and de-icing materials used during the winter months. Another requirement of the repair material is a quick-curing process that does not infringe upon its high performance. ODOT's primary concern is for the safety of the public and its employees; minimizing the time and manpower required to install the repair materials would be ideal and cost efficient. Therefore, materials with these characteristics would be ideal for this type of repair project.

1.3 Definition of Terms

ACI – American Concrete Institute

ACT – Acoustic Concrete Tester

ASTM – American Society for Testing and Materials

INDOT – Indiana Department of Transportation

ODOT – Ohio Department of Transportation

PennDOT – Pennsylvania Department of Transportation

UPV – Ultrasonic Pulse Velocity

1.4 Study Objectives

The objectives of this study were to conduct follow-up testing of the existing patches, observe and document the patch installation process, record the visual inspection of existing and newly installed repair materials, and report the field performance results using nondestructive testing methods.

This study aimed to identify which patch repair materials performed the best in the field. High performing, durable repair materials are sought after as a permanent solution to pavement and bridge deck repairs. Nondestructive testing is one method used in the determination of which repair materials should be recommended for use in ODOT's specifications for repair materials. Visual inspections are another method that was used in this determination.

1.5 Organization of This Study

This study is organized into eight chapters. The first chapter discusses the introduction, ODOT problem statement, definition of terms, study objectives, and this organization. The second chapter discusses the background and literature review. The third chapter discusses the field-testing methods including previous test methods used to test the strength and cohesion of the patch materials, the ACT, the rebound hammer, and the infrared camera. The fourth chapter discusses the repair material field performance criteria and the material selection. The fifth chapter discusses the patch installation process and considerations for the field crew when installing repair materials. The sixth chapter contains patch inspections and patch failures. The seventh chapter contains the manufacturer's recommendations for MG Krete and RepCon 928, the conditions for all patches inspected, the ACT results, and the rebound hammer results. The eighth and final chapter includes the summary, conclusion, and future research.

CHAPTER II
BACKGROUND AND LITERATURE REVIEW

This chapter includes summaries of previous research projects performed on patching roadways and bridge decks in various states across the United States and in the United Kingdom. These projects are similar to the topic of this thesis and can provide useful insight to the installation and performance of repair materials.

2.1 Indiana Department of Transportation

Indiana Department of Transportation (INDOT) sponsored research done by Purdue University. INDOT specified that early strength, high durability, and low cracking potential would be ideal characteristics for repair materials. The objectives of this research was to evaluate potential repair materials in relation to rate of strength gain, volume stability, bond, and the environment the material can be placed in (Barde, et al, 2006).

Before selecting potential repair materials to patch potholes and cracks in pavement, one must consider the expectations during and following installation of said materials. Time is an important factor when deciding which materials would be able to be prepared and installed in a short amount of time. In order to maximize efficiency of placement, the material must have rapid strength gain, allowing the structure to return to its normal activities in a short amount of time. The material must be able to withstand loads and stresses associated with the activities of the structure. It must also be able to bond to the substrate. This means the repair material must have a similar modulus of elasticity and similar, if not higher, strength of the surrounding pavement. Durability is an important factor, as the material must be able to withstand freeze-thaw cycles and resist chloride infiltration (Barde, et al, 2006).

Upon researching repair materials with the above-stated characteristics, the researchers classified the materials into three groups: cementitious mortars, polymer-modified cementitious mortars, and resinous mortars. Thirty-three different materials were requested from 22 companies. Only 11 of the 33 materials were received. In addition to the 11 materials, a mix of ASTM type II Portland cement with 2% Calcium Chloride as an accelerator was used as a baseline. All 11 materials allowed for coarse aggregate extension, and ⅜ inch aggregate was used (Barde, et al, 2006).

Several mixing procedures were used in order to determine which was optimal for use in the field. The ideal homogeneous mix was obtained by using a slow-speed right-angle hand-drill with a 5-inch tall mortar-mixing paddle. The mixing procedure for each material was different; however, the general procedure was that water was added first, then the coarse aggregate, and then the powder. After each material was mixed as directed by the manufacturer, they were poured into specimen molds and cured (Barde, et al, 2006).

The 11 materials endured rigorous laboratory testing. Some of these tests include compressive strength, flexural strength, elastic modulus, maturity meter, pullout test, shear-bond test, and ultrasonic pulse velocity meter. Since these repair materials have a variety of uses, it did not appear appropriate to rank them. The results from each test were put into a table to be used as a reference. INDOT will use this table to determine which repair material would be most ideal for the specific application as needed.

Following the laboratory testing, INDOT conducted repairs on a bridge deck due to spalling. The spalling was most likely due to unfilled saw cut notches or failure under loading. Before the repairs could occur, the repair process involves (Barde, et al, 2006):

- Preliminary inspection of damaged pavement area
- Removal of damaged concrete and surface preparation
- Mixing and installation of the repair material
- Finishing the repair material properly

As noted in this study, simply following preparation and installation procedures for repairing pavement or bridge decks may not prevent failure. The patch that was repaired in this study had been repaired the previous year.

2.2 Pennsylvania Department of Transportation

Pennsylvania Department of Transportation (PennDOT) conducted research with Pennsylvania State University on the deterioration of bridge decks in Pennsylvania. The objectives of this study were to research, test, and evaluate different patching materials to suit the needs for repairing a bridge deck (Cervo and Schokker, 2008).

In Pennsylvania's "Bulletin 15," there is a long list of PennDOT approved patching materials, organized in categories. In order to narrow the list of which materials to test, standard ASTM testing methods were used. Also, surveys regarding recommendations of which repair materials to test were sent to DOTs around the country. The only response was from Indiana's DOT, recommending Duracal, which is a rapid setting repair concrete. Six materials were chosen from "Bulletin 15," including Indiana DOT's recommendation of Duracal (Cervo and Schokker, 2008).

Each of the six chosen materials underwent various tests in accordance with ASTM testing standards. Included in these tests were compression strength, freeze-thaw using normal and salt water, slant shear, and thermal expansion and shrinkage. After the tests following ASTM standards, two patching materials were selected for more specialized testing. These two materials performed the best out of all six materials in the previous tests, which is the reason why they were chosen for the specialized tests. These tests are "durability under traffic loading and durability in chloride environments," (Cervo and Schokker, 2008). It is important that a repair material perform well in both cases, as the majority of bridge deck failures are due to heavy traffic loads, freeze-thaw cycles, and chloride penetration and corrosion of reinforcing bars within the deck.

In order to test for durability under traffic loading, two methods were used (patch separation testing and abrasion testing). Patch separation was tested using a three-point bending test. Using known loads and deflections, the durability of patched slab strips was tested and then load-deflection curves were plotted. The second method for durability under traffic loading was the abrasion test. A Mobile Model Load Simulator – 3rd scale (MMLS3) was used to repetitively tire-load the patch materials. This method also tested the abrasion-resistance of the patch materials using ASTM C 418 "Abrasion Resistance of Concrete by Sandblasting," (Cervo and Schokker, 2008).

When testing for durability in chloride environments, the patch material specimens were fitted with an electrical connection to the reinforcement to track deterioration. The specimens were subjected to 1-week dry, 1-week surface-submerged cycles. A 3% NaCl solution was used during the submerged cycle. Every two weeks, half-cell potential readings were taken, in accordance to ASTM C876. These readings gave possible locations of corrosion within the reinforcement. Following two months, the specimens were cracked to allow direct contact with the 3% NaCl solution. After 3 months, the specimens were visually inspected to determine the extent of the deterioration of the reinforcement.

The results from both methods of testing: durability under traffic loading and durability in chloride environments proved that both materials selected from

“Bulletin 15” performed well. Cervo and Schokker (2008) recommend the following procedure when preparing the pavement surface to receive a new patch:

- Mark the areas of deteriorated concrete on the bridge deck that are in need of replacement
- Saw cut around the perimeter of the marked areas, making sure that all of the perimeter angle are right angles
- Jackhammer out the area within the saw-cut until solid substrate concrete is reached
- Clean debris off of concrete and exposed rebar by either grinding or sandblasting, and then replace any rebar ties that may have been destroyed or damaged during jackhammering
- Refer to the proper mixing and material placement procedures recommended by the patch material manufacturer

2.3 United Kingdom

This literature review is a study done in the United Kingdom. The objectives of this study were to evaluate and assess the effectiveness of the current different concrete repair processes and procedures. Baldwin and King (2003) review the reasons behind deterioration of concrete structures. They include corrosion of reinforcement due to chlorination or carbonation, chemical attack, alkali-aggregate reaction, fire damage, freeze-thaw, and structural damage (Baldwin and King, 2003). The most common reason concrete deteriorates and eventually fails is due to corrosion of the reinforcement. Some causes of reinforcement deterioration include poor design, low quality concrete, not enough clear cover, and poor workmanship.

Planning repairs of a concrete structure involve multiple steps. This usually begins with a visual inspection, followed by testing and a more exhaustive inspection to reveal the reasons for and extent of damage or deterioration. If the structure requires repairs, the type of repair must be determined. This is done by selecting which repair system is necessary: (Baldwin and King, 2003)

- To restore structural integrity
- To prevent further deterioration
- To restore to its original state
- To improve its aesthetic appearance

When deciding which repair material is required for the repairs, the behavior and properties of the material must be known. This ensures that the base concrete is compatible with the repair material and can perform at its fullest. Otherwise, the results could be detrimental to the surrounding pavement (Baldwin and King, 2003).

There are a variety of patch repair material types. The set time for cementitious repair materials is influenced by the water-to-cementitious-material ratio. Adding polymers to the mixture can enhance the repair material's performance. Polymer repair materials contain many ideal qualities: high workability, rapid set time, little-to-no shrinkage, abrasion and chemical resistance, and high bond strength. Epoxy repair materials have similar characteristics as polymer repair materials (Baldwin and King, 2003).

Baldwin and King (2003) list proposed steps for hand-placing concrete repairs:

- Inspection and diagnosis
- Concrete breakout
- Cleaning reinforcement
- Coating reinforcement
- Bonding aid/chloride barrier
- Formwork
- Repair concrete and mortar
- Curing
- Concrete coating

2.4 Iowa State University

Daniel P. Frentress and Dale S. Harrington compiled the Guide for Partial-Depth Repair of Concrete Pavements (2012) for Iowa State University based on published studies regarding partial-depth repairs. They describe the three general types of partial-depth repairs: Type 1, Type 2, and Type 3 (Frentress & Harrington, 2012).

Type 1 covers all spot repairs for joints, cracks, and spalls. These spot repairs are shallow, usually no more than 2 inches (51 mm) deep and 6 feet (1.8 m) long, as the deterioration occurs in the upper portion of the slab. When spot repair areas are located 2 feet (0.6 m) or closer, the repair areas should be combined. Type 1 spot repairs happen along transverse or longitudinal cracks, joints, or spalls. The most common method used to remove unsound pavement for Type 1 spot repair is saw-and-chip. Once this method is used, a small jackhammer is used to taper the edges (Frentress & Harrington, 2012).

Type 2 includes extended-length repairs, which are greater than 6 feet in length and as deep as one-half of the slab depth. Type 2A repairs are for transverse and longitudinal joints, while Type 2B repairs are for cracking. Type 2A repairs involve re-establishing the joint. Type 2B repairs involve filling the crack with a preformed joint compression material. The preferred method of removing deteriorated pavement is milling in the case of Type 2 repairs. This is more cost-effective than the saw-and-chip method, as these repairs are much longer in length than Type 1 repairs (Frentress & Harrington, 2012).

Type 3 describes bottom-half spot repairs, which often times extend to the full depth of the slab. These repairs usually occur at a corner or edge of a pavement slab and sometimes require a full-depth repair. A Type 3 repair can extend 18 inches (0.5 m) along the centerline, but no more than 18 inches transversely into the lane. If the damage extends transversely more than 18 inches, then a full-depth repair is required. In order to make repairs, the saw-and-chip method or milling may be used (Frentress & Harrington, 2012).

Once the type of repair needed is determined, the repair area should be properly prepared. All deteriorated concrete should be removed with a jackhammer and the area should be clear of debris. Compressed air, dry sweeping, and sand or water blasting are commonly used to remove loose debris and clean the pothole prior to installing the patch repair material. Once the patch material is mixed thoroughly, it is placed slightly overfilling in the hole. The material is consolidated and the air voids are released, which reduces the volume in the repair area. The general patch material placement guidelines are listed below (Frentress & Harrington, 2012):

- Avoid installing when ambient temperatures are below 40°F (4°C)
- Use small batches
- Use vibrators to consolidate patch materials for large batches and rod or tamp smaller patches
- Match the surrounding pavement texture
- Work the patch material from the middle outwards to the edges to bond tightly

2.5 Ohio University

Researchers Munir D. Nazzal and Sang-Soo Kim of Ohio University and Ala R. Abbas, of the University of Akron, evaluated winter pothole patching methods. The throw and roll method, along with the spray injection method, were compared to the tow-behind combination infrared asphalt heater/reclaimer method. The purpose of the study was to determine whether the infrared asphalt heater/reclaimer method was more cost-effective with better performance than the other two methods used. In order to do so, this study was conducted and 60 patches were installed. The researchers observed the methods of installation, as well as the performance and survivability of each patch (Nazzal, Kim, & Abbas, 2014).

The most important factors for determining which method is optimal for installation are the location of the potholes, traffic control, and traffic flow. In an area that has high traffic flow, it is ideal to use a method that has high productivity. This allows for quick installations and less time interrupting traffic patterns. Cost is also important when deciding which method to use. The initial cost is not the only cost to consider; the "life cycle cost" includes all of the maintenance or service costs incurred throughout the patch material's life (Nazzal, Kim, & Abbas, 2014).

As part of this study, a survey was taken regarding installation and performance of the different patching methods. Of the responses received, 90% of users agreed that the infrared asphalt heater/reclaimer was more cost-effective than other methods. The majority of users agreed that the weather during installation was a major factor in performance of the patch itself. Water in the pothole could affect the bond between the patch material and the existing pavement. When patching potholes, flexible pavements usually perform better than composite pavement. Pavement type is another factor that the users mentioned could be important when patching. However, the thickness of the pavement and the aggregate size could affect the patch bond to the pavement as well (Nazzal, Kim, & Abbas, 2014):

After the survey was done and the responses analyzed, the researchers conducted the installation and testing portion of the study. Man-made potholes were created on a highway using drills. The potholes in this area were 3 to 4 feet (0.9 to 1.2 m) wide, 3 to 5 feet (0.9 to 1.5 m) long, and 3 to 4 inches (76 to 102 mm) deep. The pavement structure was composed of 6 inches (152 mm) of an aggregate subbase layer, 9 inches (229 mm) of Portland cement concrete base layer, 3.5 inch (89 mm) asphalt concrete middle layer, and 1.5 inch (38 mm) asphalt concrete top layer. Each pothole was placed at least 40 feet (12 m) from one another and cracked areas of pavement were avoided. Using all three methods of patching mentioned in this review, the patches were installed. Researchers noticed that the potholes were too clean and lacked water, compared to real potholes. The second area of repair was another highway, which had significant cracking along the edge lane. The next section of highway had damage caused by the horses that pull Amish buggies. The fourth area of repair was on a state route that had settlement issues from nearby trenches. The fifth area was another state route with settlement cause by trenches as well. The sixth and final area was to repair shoving near an intersection. The three methods were used to spot-repair damaged areas of pavement in each area, in order to evaluate each method's effectiveness (Nazzal, Kim, & Abbas, 2014).

The performance of each patch was evaluated multiple times between 29 and 188 days after placement. The Strategic Highway Research Program (SHRP) guide was used to classify any damage that the patches showed at each inspection. Six of the patches that were installed using the spray injection needed to be repaired within a month of being placed. The throw-and-roll method, as well as the spray injection method, showed that the most common distress was dishing, which is further compaction caused by traffic, causing a bowl-shaped depression. The patches that were installed using the throw-and-roll method performed better when a 0.25 inch (6 mm) to 0.5 inch (13 mm) crown was left above the pavement level. The most common distress for the infrared method was raveling, which was most likely caused by the mix being too dry and the over mixing of the material. In order to have the highest survivability and performance of patching materials, Nazzal, Kim, and Abbas (2014) recommend following these guidelines:

- The patching material must be stored in a dry place
- The proper procedure recommended by the manufacturer must be followed

- The timing of patching is critical
- The quantity of the patch materials must be monitored throughout the patching process

CHAPTER III
FIELD TESTING METHODS

3.1 Previous Methods

Prior to this study, other methods of testing were used to determine possible delamination and debonding of pavement, as well as the uniformity and overall soundness of the pavement (Lesak, 2014). The methods used in the previous study include delamination testing (the rebar test and rotary percussion), nondestructive testing (ultrasonic velocity meter), and visual inspections. The first two methods aided the previous research team in locating areas of pavement that needed to be repaired. All methods of testing were useful in that they provided information about the pavement below the surface, which could not be seen during a visual inspection.

The rebar test involves a 4 to 5 foot (1.2 m to 1.5 m) length of rebar that is tapped on different parts of suspected failing pavement to determine if there is any delamination or potential debonding occurring underneath the pavement surface. If the pavement is sound, the rebar makes a pinging noise, whereas if it is not, it makes a dull thudding sound. However, it can be difficult to differentiate between the sounds the rebar makes when tapping different types of pavement. It can also be difficult to locate where the sounds are coming from in a large test area (Lesak, 2014).

The second sounding method used to determine delamination or debonding is rotary percussion. The device used to perform this test is called a Delam 2000. This device has two rotating toothed disc-like wheels attached to a long pole. The Delam 2000 is rolled over the pavement in question and makes a ringing noise if the pavement is sound. If the Delam 2000 makes a hollow sound, the pavement underneath it most likely has delamination failure. Both the rebar test and rotary percussion test were used to locate the areas of pavement that needed replacement or repair as well as the size of the repair areas (Lesak, 2014).

The third method used previously is ultrasonic pulse velocity (UPV); this method is useful in determining the uniformity of pavement within the testing area. The UPV contains two transducers; one is a transmitter and the other is a receiver. The transmitter and receiver are placed at a specific distance apart and are coated with a coupling agent. This ensures the ultrasonic waves can pass from the UPV into the pavement without interruption. When the wave is sent into the pavement, the UPV measures the time it takes for the wave to pass from the transmitted to the receiver (ACI Committee 228, 2013).

The final method used was visual inspection, which provided the most information regarding the condition and performance of the patch materials. Visual inspections were conducted during the previous study, as well as this one. The previous inspections were extremely helpful in determining the durability and condition of each patch; the research team recorded important details, such as possible delamination or the presence of cracks. The visual inspection of each patch is located in Chapter VI.

3.2 Acoustic Concrete Tester

The Acoustic Concrete Tester, or ACT, is a nondestructive technique that can be used to determine thickness in concrete slabs, walls, and foundations. The ACT can also detect flaws in concrete, such as air voids. The ACT has two probes that are coated with an adhesive putty that allows it to have a better surface connection to the concrete that is being tested. When the ACT is in use, the transmitting probe sends out a broadband input wave into the concrete. The wave reflects through the concrete and to the receiver probe. The ACT then determines the thickness of the concrete and displays it on the screen (ASTM C1383 -15).

The ACT operates under the same fundamental principles as the wave propagation theory and the resonance frequency method. Essentially, there is a transmitting probe, which sends out a short duration high voltage pulse wave. This wave travels through a specimen and is received by another receiver probe. The receiving probe uses high digitizing frequencies and real time Fast Fourier Transform (FFT) to determine the dominant frequency, which leads to the determination of the thickness of the test specimen. The time duration in which the wave travels between the probes through the specimen is also recorded and used to identify the thickness. The compression waves being emitted consist of a primary P-wave and a shear S-wave. These waves travel is a spherical motion between the transmitter and receiver probes. The P-wave speed is a critical measurement that was measured by the ACT during each individual test (Inspection Instruments, Inc., 2008).

The ACT uses the P-wave speed and the resonant frequency response to convert and identify the thickness of the specimen. The wave speed can be assumed in some situations; however, the results are not as accurate or as precise as they would be if it were measured with each test. Flaws within the specimen such as horizontal cracking, large air voids, and/or large amounts of air voids can drastically affect the accuracy of this test. The flaws would cause the P-wave speed to increase or decrease rapidly which would directly alter the readings (Inspection Instruments, Inc., 2008).

Figure 1 below shows the ACT screen after a reading has been taken. The estimated thickness is in the upper left corner of the screen. The ideal graph shows one prominent peak, which is when the wave reflects off of the bottom of the material. If there are coupling issues, the graph will not contain any dominant peaks. The frequencies would appear to be consistent with each other, creating an almost horizontal line.

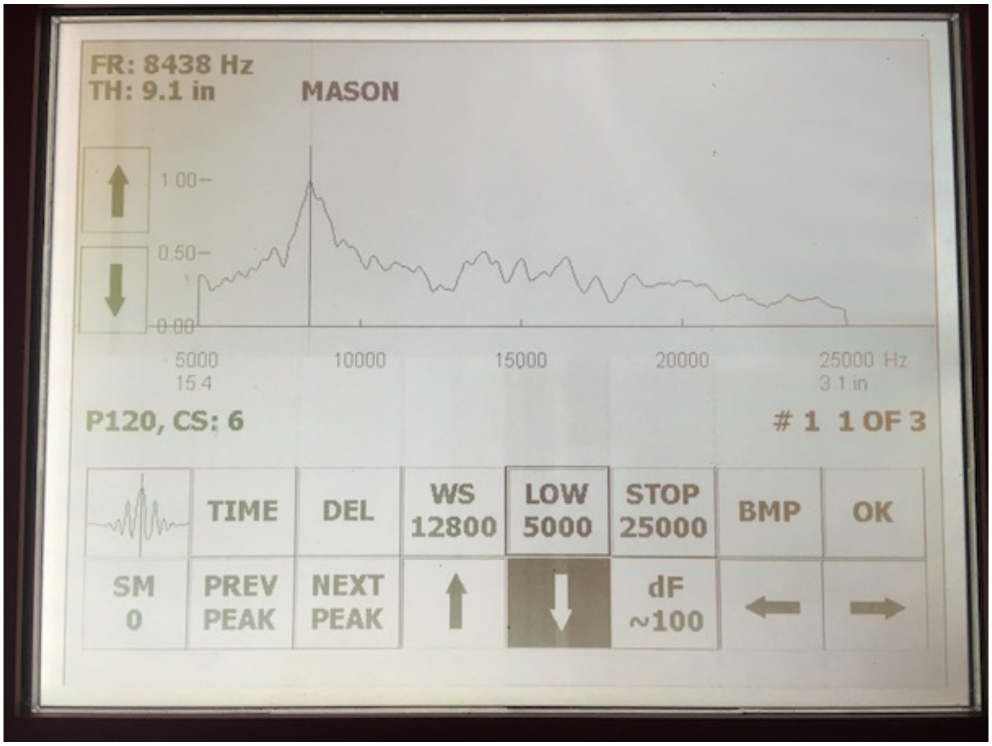

Figure 1: The ACT screen displaying the thickness of the pavement slab.

3.3 Rebound Hammer

One of the items of equipment used in the patch analysis was the rebound hammer. A rebound hammer contains a spring, hammer, and plunger, which are all enveloped by the hard outer body. In order to use a rebound hammer, the plunger must be depressed fully and placed firmly against the concrete surface. The hammer is locked at the top of the plunger, while the housing of the rebound hammer lowers to the concrete surface, which extends the spring. Once the plunger reaches its end of travel, a mechanism releases the hammer. The hammer drops and the plunger strikes the concrete surface, rebounding as the spring compresses. The rebound number is recorded each time the rebound hammer hits the surface. The value of a rebound number is between 10 and 100 and is a measure of the surface hardness, not the strength of the concrete. However, the rebound hammer is typically used to estimate the strength of a concrete surface. Therefore, depending on the surface characteristics of the concrete specimen being tested, the results of this method can vary drastically. These characteristics include, but are not limited to, hard aggregate, soft aggregate, sizable air voids, and reinforcing steel at or near the surface of the specimen being tested. In these situations, the hardness or softness of the abovementioned characteristics would impact the rebound (ASTM C805/805M – 13, 2013).

While performing this test, the rebound hammer should be depressed ten times at ten different locations in a small area on the specimen surface. This is done to reduce the possibility of error while collecting data. The texture of the surface is another factor that needs to be considered while performing this test; a rough surface should be smoothed before conducting the rebound hammer test. Surface hardness develops at a different rate than the strength; therefore, the time at which the specimen is tested may yield various results it ages. When a concrete specimen is compressed, the rebound number will be higher than if the specimen is not under load. The average coefficient of variance is around 10% but can be as high as 20% (ASTM C805/805M – 13, 2013).

Advantages of using a rebound hammer are that it is simple to use and inexpensive compared to other nondestructive tests. Disadvantages include not having a direct correlation to strength of the concrete and the effect of the characteristics of the soft and hard aggregates, air voids, and reinforcing steel (ASTM C805/805M – 13, 2013).

3.4 Infrared Camera

An infrared camera was used to record the temperatures of the patching materials during installation. Table 1 below shows the temperatures for the five patches that were installed in June 2015. The temperatures were taken initially, when the patching material was first placed, then 30 minutes after placement, and the high temperature was recorded as well. Both MG Krete and RepCon 928 had high initial temperatures that continued to climb as time went on. This can be attributed to the high ambient temperature and humidity when the patches were installed. Although the patches were installed after 10 pm, the surrounding pavement was still very warm from being in direct sunlight during the day. The high ambient and pavement temperature played a role in the reactions that occurred when the patching materials were mixed. It can also be attributed to the fact that the materials, namely MG Krete, set very quickly, within a few minutes.

Patch Name	Patch Material	Initial Temperature, F	Initial Temperature, C	30 Minute Temperature, F	30 Minute Temperature, C	High Temperature, F	High Temperature, C
D1	MG Krete	96.0	35.6	117.0	47.2	136.0	57.8
D2	Mg Krete	97.0	36.1	104.0	40.0	138.0	58.9
D3	RepCon 928	81.0	27.2	92.0	33.3	97.0	36.1
D4	RepCon 928	81.0	27.2	80.0	26.7	86.0	30.0
D5	RepCon 928	86.0	30.0	84.0	28.9	102.0	38.9

Table 1: Temperature data at different time intervals after patch installation.

CHAPTER IV

SELECTION OF REPAIR MATERIALS

4.1 Repair Material Field Performance Criteria

There are several important factors determine the field performance criteria for repair materials: durability, stability, cost-effectiveness, and high early strength. The selected repair materials must bond to the existing substrate and contain no cracking on the surface or within the material. They must also possess qualities that allow them to remain intact throughout freeze-thaw cycles. Repair materials should possess these characteristics in order to be selected for this project. In the state of Ohio, the changing of the seasons and varying temperatures contribute to the failure of pavements. Because this study took place in Ohio, repair material products are should contain sulfate-resistant characteristics (Sommerville, 2014).

Roadway and bridge deck maintenance is a frequent activity in Ohio, and in order to keep costs down, ODOT must select repair materials that are cost-effective. However, this does not mean ODOT selects the least expensive repair product on the market. User and worker safety is of utmost importance; efficiency is key in roadway repair and maintenance. When repairs must occur, it causes a disruption in traffic patterns. In order to keep traffic flowing and safety a priority, patch materials that are being installed should have early high-strength. This means that the patch material gains strength quickly, allowing the repaired roadway to resume its normal activity within a few hours (Sommerville, 2014).

4.2 Selection of Repair Materials

At the beginning of this project, ten high performance repair materials were selected for potential field and laboratory testing. Of those ten, six were chosen for field installation based on how well they met the field performance criteria previously stated. The six repair materials are Delpatch, FastSet DOT Mix, FlexSet, MG Krete, RepCon 928, and SR2000. These materials endured rigorous testing in the laboratory as well as in the field (Amini, 2015).

4.2.1 Delpatch

Delpatch Elastomeric Concrete, a polyurethane patching material made by D.S. Brown, is comprised of sand, fiberglass, two types of liquid activator, and a primer. Delpatch was primarily specified for use on airport runways to repair spalls and cracks, but can be used in concrete repairs. It is easy to install in that Delpatch is self-leveling and has a rapid cure time; traffic can be reopened within an hour of the final pour. The cost of Delpatch is $232.43 per cubic foot (0.028 m^3) (D.S. Brown, 2016).

Prior to installation, the repair area should be saw cut and jackhammered so that all unsound concrete can be removed. The area where Delpatch is to be applied should be coated with the primer prior to adding the Delpatch mixture. The primer must cure for 30 minutes before the product is added to the patch area. The sand and fiberglass should be gradually mixed into the liquid activators in a Hobart, drill, or pail mixer for three minutes. Once the primer has cured, the mixture can be added to the patch area. The set time for Delpatch is about 10 minutes (D.S. Brown, 2016).

4.2.2 FastSet DOT Mix

Quikrete's FastSet DOT Mix is a fiber-reinforced, rapid setting repair material that meets ASTM C928 Category R3 for high performance repair materials. It may be extended with up to 25 lb (11.3 kg) of gravel per 55 lb (24.9 kg) bag of the DOT Mix. The cost of FastSet DOT Mix is \$11.32 per cubic foot (0.028 m^3) (Quikrete, 2012).

FastSet DOT Mix is a powder that is added to water and mixed for three minutes to form a workable material. When placing FastSet DOT Mix, it should be lightly rodded to avoid the formation of air bubbles. During cold weather installation, it is specified that hot water should be used. On the contrary, in hot weather installation, ice water should be used. FastSet DOT Mix has a 30-minute working time before it sets (Quikrete, 2012).

4.2.3 FlexSet

FlexSet was created by Roklin Systems Incorporated as a rapid repair material for airport runways. FlexSet can be used in cold weather installation, which is one reason why it was chosen for the winter installation. It also can be used in both asphalt and concrete pavements. FlexSet costs $235 per cubic foot (0.028 m^3) (Roklin Systems Inc.).

The FlexSet kit contains two liquid activators, as well as, polymer-coated sand and a sand topping. The first liquid activator is gradually added into the polymer salt. Once it is thoroughly mixed, the second liquid activator is added gradually until it is thoroughly mixed. After the material is added to the repair area, the sand topping can be added to the discretion of the field crew. FlexSet has a working time of up to 12 minutes (Roklin Systems Inc.).

4.2.4 MG Krete

The fourth chosen material is MG Krete, produced by Imco Technologies Inc. MG Krete is an early high-strength, magnesium phosphate-based concrete repair material that is best used in structural applications. It is comprised of powder and a liquid activator. It can be installed in most weather conditions. Its ideal uses include driveways, pothole repair, airport runways and aprons, stairs, bridges, and parking decks. MG Krete is not susceptible to shrinkage, creates a "tenacious bond," and is impervious to moisture, salt, gas, and oils (Imco Technologies Inc., 2012).

An advantage of using MG Krete for concrete repair is its ability a cure in any weather condition. In addition, it can be troweled vertically or horizontally, and it can be returned to service in as little as 30 minutes after being installed. MG Krete is said to have a 3000 psi (20.7 MPa) compressive strength within 2 hours after set (Imco Technologies Inc., 2012).

MG Krete is best applied on a rough surface, and the repair area must be clean, dry, and free of debris. If using MG Krete in temperatures over 68°F (20°C), a retarder should be used to delay the set time; on the contrary, in temperatures under 50°F (10°C), an accelerated admixture should be used (Imco Technologies Inc., 2012).

There are two components involved when mixing MG Krete, which are liquid and powder. Water should never be added to this mixture. The mix ratio is one bag of powder component to one container of liquid component and can be adjusted to the application for which it is needed. MG Krete costs $122.22 per cubic foot (0.028 m^3) (Imco Technologies Inc., 2012). MG Krete usually sets within 15 minutes and must be textured using a rake prior to setting.

4.2.5 RepCon 928

RepCon 928 is a concrete repair material that is best used when the scope of work for a project requires an accelerated set time due to time restrictions. The characteristics of RepCon 928 consist of a concrete repair mortar hat has corrosion resistance and is polymer-modified and fiber-reinforced. It is commonly used on bridge decks, highway pavements, and concrete flooring. Some features of RepCon 928 include air entrainment for freeze-thaw durability, the ability to apply the repair material vertically with forms or horizontally, and the ability to set within an hour to allow for foot traffic. RepCon 928 costs $57.36 per cubic foot (0.028 m^3) (SpecChem, 2015).

RepCon 928 requires only its powder component and water to provide an easily workable mixture. Cold water must be used to mix RepCon 928 if the temperature is above 85°F (29°C). When mixing RepCon 928 in a batching mixer, the water should be added first, and then the powder mixture is to be added gradually until it is fully mixed. After both components are completely added, the mixture is mixed for three minutes (Lesak, 2014).

Before installing RepCon 928, the repair area must be prepared accordingly. It must be free of any debris or contaminants, the edges should be square and saw cut, and the surface should be manually roughened. Any corrosion from reinforcement should be removed prior to installing RepCon 928 (SpecChem, 2015).

When mixing RepCon 928 before installation, a low speed drill or mortar mixer should be used. Depending on the required consistency of the RepCon 928, the amount of water to be used ranges from 4.75 pints to 5.25 pints (2.25L to 2.48L). The manufacturer recommends adding the water first to the mixer, then slowly mixing in the RepCon 928 mixture. Once all of the powder mix is added, the entire mixture is mixed for 2 to 3 minutes. When repairing areas deeper than 2 inches (50.8mm), it is recommended to add aggregate to the RepCon powder (SpecChem, 2015).

Once the RepCon is mixed, it should be troweled into the repair area and be flush with the existing concrete. RepCon 928 should be finished by hand troweling once it is surface hard (SpecChem, 2015).

4.2.6 SR-2000

SR-2000, developed by Southeast Resins Inc., was chosen because it can be used to repair both concrete and asphalt. SR-2000 is a polyester resin that is strong, yet flexible. The SR-2000 kit includes a liquid resin and #30 grit aggregate. SR-2000 costs $175 per cubic foot (0.028 m^3) (Lesak, 2014).

The location where the patch will be installed should be primed with the resin prior to installation. SR-2000 can be installed in temperatures ranging from 35°F to 120°F (2°C to 50°C) and will not soften in direct sunlight. SR-2000 is able to accommodate traffic in less than two hours after set. After SR-2000 is installed, a nonslip topcoat can be can be added if desired (Superintendent's Profile, 2003).

CHAPTER V

PATCH INSTALLATION

5.1 Patch Installation Process

On June 22, 2015, the research team traveled to Mason, Ohio, to meet with the ODOT team who was working on this project. The area of the bridge deck that was under construction was Exit 2A Western Avenue/Liberty Street on Interstate 75. The work crews headed out around 7:30 pm to set up lane closures. The work began at 10:58 pm with the ODOT crews jackhammering the area around the potholes on the bridge. Table 2 below shows the names and locations of the five patches that were installed. Figure 2 shows the repair area after the unsound concrete has been removed using a jackhammer.

Patch Name	Patch Location
D1	N 39.120136 E -84.535689
D2	N 39.120069 E -84.535622
D3	N 39.119811 E -84.535598
D4	N 39.119810 E -84.535589
D5	N 39.119571 E -84.535571

Table 2: Patch names and locations.

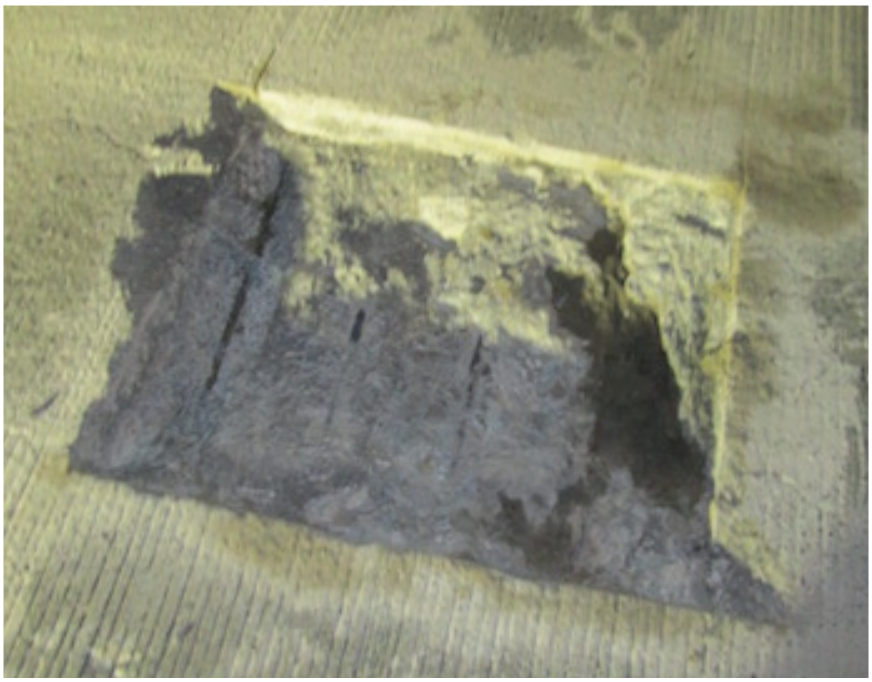

Figure 2: One of the repair areas after being jackhammered.

The first repair area was located at N 39.120136 E -84.535689. The surrounding bridge deck was in good condition. The first patch was located partially in the right wheel path of the fourth lane from the left edge line, at the edge of the approach and bridge deck joint. It took the ODOT crew approximately 10 minutes to jackhammer the repair area. The dimensions of the first patch were 12 inches by 21 inches by 2 inches deep (305 mm by 535 mm by 50 mm). The material used to fill the patch was MG Krete. The MG Krete gave off ammonia gas and bubbles began forming after the patch was put in place.

At the time of the pour, the outside temperature was 81 degrees Fahrenheit (27 degrees Celcius). The ODOT road crew mixed the MG Krete using two liters of the liquid component and one half bag of dry component. In a typical MG Krete batch, four liters of liquid component and one whole bag of dry component were used. The first batch of MG Krete that was mixed in half batches; this is because the first half batch was dry and crumbly. The second half batch was more liquid-like, which is closer to the desired consistency of the MG Krete. Once both half batches were poured into the first patch area, the area was textured with a rake to ensure maximum traction for vehicle tires. However, the MG Krete set very quickly, within a few minutes of the first batch being poured. This made it very difficult to texture the patch. After the ODOT crew installed the first patch, an infrared camera was used to record the initial temperature, the high temperature, and the temperature after 30 minutes of the MG Krete. Figure 3 shows an MG Krete patch after it has been finished and raked.

Figure 3: The MG Krete set very quickly, causing difficulties raking the patch area.

The second repair area was located at N 39.120069 E -84.5356217. The surrounding bridge deck pavement was in good condition. The second patch was located in the left wheel path in the third lane from the left edge line, near the expansion joint of the bridge deck. It took the ODOT crew approximately 24 minutes to jackhammer the repair area. The dimensions of the second patch were 29.5 inches by 41 inches by 2 inches deep (750 mm by 1042 mm by 50 mm). The material used to fill the patch was MG Krete. The work on the second repair area began at 11:11 pm. Because of the larger patch size, it took 3 batches of MG Krete to fill the repair area. The batches were placed in layers to promote consistency in the patch material. The MG Krete set within a few minutes, making it not very workable. The second patch, much like the first, was difficult to rake and texture. Figure 4 shows an MG Krete patch before it has been raked.

Figure 4: The repair area after being finished and before being raked.

The third repair area was located at N 39.119811 E -84.535598. The surrounding bridge deck area was in good condition. The third patch was located in the right wheel path in the third lane from the left edge line. It took the ODOT crew approximately 10 minutes to jackhammer the repair area. The dimensions of the third patch were 16 inches by 15 inches by 2.5 inches deep (406 mm by 381 by 64 mm). The material used to fill the patch was RepCon 928. The first batch of RepCon 928 was not mixed thoroughly, resulting in uneven consistency. As a result of this, the RepCon 928 was removed from the repair area and was remixed more thoroughly. The first batch of RepCon 928 was mixed by adding half of the required amount of water to the mixer, the entire bag of RepCon 928, and then the remaining water. According the RepCon 928 manufacturer, the proper order of adding the materials to the mixer are as follows: the total amount of required water for the batch, then the RepCon 928 powder is to be added slowly while continuously being mixed. A second batch of RepCon 928 was needed to fill the remainder of the repair area. The second batch was soupy, as too much water was added to half of a bag of RepCon 928 mix. The patch was left to set for 15 minutes before being raked to add texture. Figure 5 shows the work crew members adding another batch to the repair area.

Figure 5: Multiple batches were required to fill the large repair area.

The fourth repair area was located at N 39.119810 E -84.535589. The surrounding bridge deck area contained two cracks running laterally across the patch area. The fourth patch was located in the third lane from the left edge line. It took the ODOT crew approximately 25 minutes to jackhammer the repair area. The dimensions of the fourth patch were 35 inches by 28.5 inches by 3.5 inches deep (889 mm by 724 mm by 89 mm). The material used to fill the patch was RepCon

928. The first batch was the remaining half of RepCon 928 mix from the third patch. The first batch also had too much water added, resulting in a soupy mix. The second batch was mixed properly and had good consistency. The third and fourth batches also had good consistency. The third batch had already set by the time the fourth batch was placed. For the fourth patch, 5.5 bags of RepCon 928 powder were used. The fifth and final batch was soupy as too much water was added to the mix. Figure 6 shows a crew member finishing each layer after every batch has been poured into the repair area.

Figure 6: Finishing one of the large repair areas.

The fifth and final repair area was located at N 39.19571 E -84.535571. The surrounding bridge deck area contained multiple small potholes and patches on the other side of the expansion joint. The fifth patch was located in the third lane from the left edge line, near the expansion joint. It was located on the right side of the lane, near the right wheel path. It took the ODOT crew approximately 45 minutes to jackhammer the repair area. The dimensions of the fifth patch were 93 inches by 68 inches by 3.5 inches deep (2362 mm by 1727 mm by 89 mm). The material used to fill the patch was RepCon 928. It took 28 batches of RepCon 928 to fill the pothole, one layer at a time. The majority of the layers were of good consistency, while a few were dry and clumpy. Halfway through mixing all of the batches, there was a change in the field crewmembers mixing the batches. The first batch mixed by the new mixer was too dry and clumpy; it was remixed and water was added to make it more workable. Table 3 below shows each batch and its consistency. Table 4 shows the patch dimensions, area, volume, and time to jackhammer. Table 5 shows the temperatures of each patch during installation.

Batch No.	Consistency
1	Good
2	Good
3	Good
4	Slightly oversaturated
5	Good
6	Good
7	Good
8	Good
9	Good
10	Good
11	Good
12	Slightly oversaturated
13	Good
14	Good
15	Good
16	Slightly oversaturated
17	Clumpy, dry*
18	Good
19	Oversaturated
20	Slightly oversaturated
21	Slightly dry
22	Oversaturated
23	Good
24	Slightly stiff
25	Oversaturated
26	Stiff, dry
27	Stiff
28	Stiff, clumpy

Table 3: The consistencies of each batch for the fifth patch, D5.

Patch Name	Patch Dimensions, inch	Patch Dimensions, mm	Area of Patch, feet^2	Area of Patch, m^2	Volume of Patch, feet^3	Volume of Patch, m^3	Time to Jackhammer, minutes
D1	12 x 21 x 2	305 x 535 x 50	1.75	0.163	0.292	0.008	10
D2	29.5 x 41 x 2	750 x 1042 x 50	8.40	0.782	1.400	0.039	24
D3	16 x 15 x 2.5	406 x 381 x 64	1.67	0.155	0.347	0.010	12
D4	35 x 28.5 x 3.5	889 x 724 x 89	6.93	0.644	2.020	0.057	25
D5	93 x 68 x 3.5	2362 x 1727 x 89	43.92	4.079	12.810	0.363	45

Table 4: The patch dimensions, area, and volume, as well as the time to jackhammer each patch.

Patch Name	Patch Material	Initial Temperature, F	Initial Temperature, C	30 Minute Temperature, F	30 Minute Temperature, C	High Temperature, F	High Temperature, C
D1	MG Krete	96.0	35.6	117.0	47.2	136.0	57.8
D2	Mg Krete	97.0	36.1	104.0	40.0	138.0	58.9
D3	RepCon 928	81.0	27.2	92.0	33.3	97.0	36.1
D4	RepCon 928	81.0	27.2	80.0	26.7	86.0	30.0
D5	RepCon 928	86.0	30.0	84.0	28.9	102.0	38.9

Table 5: The temperature data at different time intervals.

5.2 Previous Patch Installations

The 85 patches that were visually examined and tested using nondestructive methods were installed in a previous project conducted in 2014. The installations of these patches were done during different weather conditions; 14 patches were installed during the winter and the remaining 71 patches were installed during the summer. The time frame that was chosen was specific, as some of the repair materials were noted to perform well during adverse weather conditions (Lesak, 2014).

The winter installation took place on March 6 and 7 in 2014. The repairs were made on State Route 35 near Xenia, Ohio. Two patching materials were installed in 14 repair areas. The two materials installed were FlexSet and MG Krete, as both manufacturers claim that these materials can be installed in temperatures as low as 14°F (-10°C). The bridge deck was patched first, with FlexSet and MG Krete patches side by side, which spanned an entire lane. Along with these two patches, two more patches were installed near the bridge deck using FlexSet. It was chosen because the repair area was within asphalt; MG Krete is not meant for asphalt repair. The remaining 10 patches were installed on March 7 within concrete pavement. Five of the patches were repaired with FlexSet and the other five with MG Krete (Lesak, 2014).

The summer installation took place on June 25, 26, 30, and July 1 in 2014. The repairs were made on State Route 35 traveling eastbound. During this time, 71 patches were installed with four different repair materials: Delpatch, FastSet DOT Mix, RepCon 928, and SR-2000. One patch material was installed per each day during the installation (Lesak, 2014).

On June 25, the first day of installation, 19 patches of SR-2000 were placed. SR-2000 was chosen as the first material to be used during the summer installation, as it was the only one that could be installed in asphalt. The first six patches of SR-2000 were placed within asphalt at mile marker 14.3. The remaining 13 patches were installed within concrete pavement at mile marker 16.1. On June 26, Delpatch was used to install 18 patches within concrete. The installation of Delpatch began at mile marker 16.1, immediately following the SR-2000 patches. A representative for D.S. Brown, the manufacturer of Delpatch, was present to ensure that the product was being installed correctly. On June 30, FastSet DOT Mix was used to install 18 patches within concrete pavement. The first six patches were installed at mile marker 16.1, immediately east of the Delpatch patches. The remaining 12 patches were installed near the 18.3 mile marker. On July 1, the last 16 patches were installed using RepCon 928. These patches were installed in concrete pavement, directly east of the FastSet DOT Mix patches at mile marker 18.3 (Lesak, 2014).

After the installation of the 85 patches occurred, the research team spoke to the field crew about their opinions of the six different products they installed. The crew stated that MG Krete and RepCon 928 were easy to work with and install.

However, Delpatch was extremely difficult to work with and finish, as well as being sticky, which made it challenging to clean out of the mixer (Lesak, 2014).

5.3 Considerations for Field Crew

This section contains the considerations for the field crew when installing high performance repair materials. Diverting from the manufacturer's recommendation for the procedure for mixing and installing patching materials could result in debonding or failure of the material and the pavement surrounding it. For both MG Krete and RepCon 928, the manufacturer's recommendations are located in sections 7.1.1 and 7.1.2, respectively.

Another important aspect for installing patching materials is the preparation of the patching area and following the batching procedures properly. Prior to mixing and placing the patching materials, the pavement that is to be replaced should be saw cut in square shapes with straight, neat edges. Often times, the crew does not remove enough of the damaged pavement material. If the reinforcement is exposed when jackhammering the degraded material, all of the concrete must be removed from the reinforcement before placing the patching material. If the reinforcement is not cleaned of concrete, the new patching material will not bond to the reinforcement and it will not serve its purpose.

The field crew should not rush to complete a job; this could result in errors and could affect the patching material's performance. When mixing batches of the patching materials, the powder component should be added gradually. The mixture should be mixed for the recommended amount of time. A few of the batches in this study were not mixed thoroughly or properly. Some of the batches were dry and crumbly, while others had too much water or liquid component.

The research team encountered problems with placing the patching materials in larger patches in a timely manner. The final patch, D5, which was installed during this study, required 28 separate batches of material to fill the patch area. The patching material began to set before the next batch was placed. This compromised the uniformity of each batch layer, and most likely contributed to the failure of the patch. Using pea gravel to slow the cure of the patching material may give the field crew more time to mix the next batch or finish each layer. Retarders or accelerators should be used during extreme temperatures to assist with the curing process. The patching materials installed during this study set quickly, most likely because of the warm ambient temperature and high humidity. The quick set time made it challenging for the field crew to finish the surface of the patches. The finishing process is important because it guarantees the surface of the patch is flush with the surrounding pavement, it removes air voids that could lead to spalling, and it acts as a seal against contaminants that are on the roadway (*Construction Administration Manual of Procedures*, 2013, p. 255). When placing the patching materials, a chute must be used if there is more than a 4-foot (1.2 meter) drop. This prevents the materials from segregating and maintains the mixture's uniformity (*Construction and Material Specifications*, 2013, p. 322).

CHAPTER VI

PATCH INSPECTIONS

6.1 Patch Inspection and Testing

The research team traveled to Xenia, Ohio in June 2015 and March 2016 to conduct testing on the new and existing patches. The team used the ACT and rebound hammer to carry out the testing. Photographs of each patch were also taken. Along with the ACT and rebound hammer, the research team visually observed each patch and noted its condition.

6.2 June 2015 Inspection

On June 4, 2015, the research team traveled to Xenia, Ohio in order to inspect patches that were installed the previous year. Dr. Miller from the University of Cincinnati accompanied the team to the area of highway that the patches were installed in 2014. The patch areas were filled with various materials; MG Krete, Flex Set, SR2000, Delpatch, FastSet DOT Mix, and RepCon 928. The research team conducted visual and analytical testing on the existing patches. The equipment used to physically test the patches was the Acoustic Concrete Tester (ACT) and rebound hammer. The team inspected and tested 85 patches of the above-mentioned materials to determine which held up the best during the freeze-thaw cycles. Figure 7 below shows the research team testing the patches with the ACT.

Figure 7: The research team testing a patch with the ACT.

6.3 December 2015 Inspection

On December 17, 2015, Dr. Miller and Mohammad Asghar of the University of Cincinnati completed a visual inspection of all 85 patches in Xenia, Ohio. The patches were photographed; the pair reported that approximately 85% of the patches were in good condition. Most of the patches held up well; however, the ones surrounded by asphalt deteriorated. An alternative patching material should be used for repairing asphalt pavement. Figure 8 shows a good example of an MG Krete patch. Figure 9 shows an SR-2000 patch with cracking and deteriorating asphalt surrounding it. Figure 10 shows a good example of a previously installed RepCon 928 patch.

Figure 8: A good example of an MG Krete patch.

Figure 9: The asphalt deteriorating around a patch. The patch material is SR-2000.

Figure 10: A good example of a patch made from RepCon 928.

6.4 March 2016 Inspection

On March 21, 2016, the research team traveled back to Xenia to conduct another visual inspection on the previously installed patches and the newer patches installed last summer. Dr. Miller and Mohammad Asghar, who assisted with the visual inspection and nondestructive testing of the patches, accompanied the team. The team once again used the rebound hammer and ACT to determine the strength and thickness of the patches. The majority of the patches survived the freeze-thaw cycle; however, the winter in this area was much milder than usual. A few of the patches contained cracking; the patches that cracked or failed appeared to be the result of the failure of the asphalt surrounding the repair area.

The team inspected the 85 previously installed patches on Interstate 35 in the morning of March 21 and went to inspect the newer patches on the Interstate 75 bridge before the Liberty Street exit in the evening. The team also tested the five patches that were installed in the summer of 2015 using the ACT and the rebound hammer.

Upon retesting the 85 patches in addition to the 5 on the Interstate 75 bridge deck, the team also conducted a final visual inspection of the patches and the surrounding pavement. The asphalt surrounding some patches showed the same, if not more, deterioration. As a result, it is evident that a different patching material is required in order to repair areas within asphalt. The other patches that were surrounded by concrete appear to have held up well; this past winter did not seem as cold or harsh as in previous years, which may be a factor in the preservation and condition of the patches. Figure 11 shows asphalt deteriorating around a patch. Figure 12 shows debonding of a patch. Figure 13 shows an SR-2000 patch with heavy cracking.

Figure 11: An example of a patch within asphalt that is showing signs of failure with cracking and deterioration around the patch material.

Figure 12: Another example of a patch showing debonding.

Figure 13: The SR-2000 patch has failed near the bottom right corner. The area has been patched with another material that is not preventing further failure of the patch.

The research team also conducted a visual inspection of the patches installed on the Interstate 75 bridge. The visual inspection concluded that three of the five patches did not hold up well. Patch D3 had deep cracking over a quarter of the patch area in the upper left corner. Patch D4 also had deep cracks, on the lower right corner of the patch. The fifth patch, D5, actually failed before the final visual inspection occurred; the field crew had to quickly repair the part of the patch that failed with Durapatch material. Durapatch is a high strength cement mortar that is used in patch repairs. It is best used in humid, cold, or wet conditions (LMCC, 2008). The five patches that were installed in June 2015 are just a few of many patches and repair areas located on this particular bridge. The failure of these patches is quite possibly the result of substrate failure, not necessarily failure of the patching material. Figure 14 shows the cracking occurring on D3. Figure 15 shows a large piece of material missing from the bottom right corner of patch D4. Figure 16 shows patch D5 with the Durapatch material on the right half.

Figure 14: Patch D3.

Figure 15: Patch D4.

Figure 16: Patch D5. The right half of the patch contains the Durapatch material.

6.5 GRE-35-0963L US 35 Patch Failure

On December 8, 2015, ODOT District 8 informed the research team that one of the previously placed patches on US 35 gave way completely. The patch area left a full depth hole in the bridge, requiring immediate repair for the safety of the road crew and the drivers on the road. The area was immediately repaired; it should hold temporarily. The whole area will be replaced in the spring of 2016 with an overlay project. The figures below show that there are multiple repair areas that are cracking and spalling, therefore, the entire area should be repaired for safety. Figure 17 shows the extent of failure of patch #1. Figure 18 shows that a full-depth repair is necessary. Figure 19 shows patch #1 after it was repaired.

Figure 17: The failure of this patch is shown on bridge GRE-35-0963L on US 35 in Mason, Ohio.

Figure 18: The complete failure of the patch is shown.

Figure 19: The area has been temporarily repaired and will be replaced with an overlay project in Spring 2016.

CHAPTER VII

RESULTS AND OBSERVATIONS

7.1 Manufacturer's Recommendations

The batching procedures explain the recommended amounts of each component required. However, the amount of each component can be adjusted to suit the need of the project. Both MG Krete and RepCon 928 manufacturers suggest using ½ inch (13 mm) or smaller aggregate for deeper patches. This is done in order to help distribute heat during the thermodynamic process, which the patching materials undergo. No additional water should be added to the batches when placing the patch materials; MG Krete requires no water when mixing, only the dry and liquid component. If aggregate is added to the batches, it should be saturated surface dry (SSD). This ensures that the aggregate is not absorbing additional liquid needed for the mixture or contributing extra liquid to the mix.

7.1.1 MG Krete

The MG Krete manufacturer recommends only using up to 40% aggregate in the mixture. It is also recommended that the aggregate be pre-damped when mixing with MG Krete. MG Krete has a quick set time of only 15 minutes in optimal ambient temperatures; the aggregate helps to slow down the cure by distributing the heat evenly throughout the mixture. In order to mix MG Krete, Part B is mixed first then aggregate then Part A. Part A is the dry mix portion of MG Krete. Part B is the liquid portion of MG Krete. It is comprised of a liquid activator that is extremely important in creating the exothermic reaction that begins the cure of MG Krete.

7.1.2 RepCon 928

Upon speaking to a RepCon 928 manufacturer representative, the ideal amount of pea gravel to be added to the mixture is 50% of the weight of the amount of RepCon 928 being used. The manufacturer also recommends pre-dampening the aggregate so that it does not absorb some of the water that is added to the mixture, which can negatively affect the patch material's strength. The order of materials to be added to the mixer is as follows: water, then aggregate, and then the RepCon 928 powder. Each material should be added gradually to ensure the materials are mixed thoroughly. Once all materials are added to the mixer, the mixture is mixed for 3 minutes before being poured into specimen molds.

7.2 Patch Conditions

This section includes more detailed information and pictures regarding the condition of the patches after they have endured at least one freeze-thaw cycle.

Previously installed patches have gone through more than three freeze-thaw cycles. In order to describe the condition of these patches, the Federal Highway Administration's Distress Identification Manual was used. Most of the cracking damage could be classified by severity: low, moderate, or high. Longitudinal cracking is generally parallel to the pavement centerline. Transverse cracking is perpendicular to the pavement centerline. Block cracking is a pattern that forms block or rectangular-like shapes. Corner breaks usually occur at a 45-degree angle with the direction of traffic. Durability cracking, or d-cracking, are crescent shaped cracks that occur near other cracks or joints. Spalling is described as the breaking or chipping of the pavement surface layer, exposing the pavement directly below. Map cracking is a series of random cracks interlacing with each other that occur on the upper surface of pavement. Blowouts are shattered pieces of pavement that become loose from the substrate (Miller & Bellinger, 2003).

7.2.1 Delpatch

The Delpatch patches did not show any cracking or surface damage during the June 2015 and March 2016 inspections and testing. The surface texture of a few patches appears to be slightly worn, but that is expected with daily traffic use. Figure 20 shows an example of a Delpatch patch.

Figure 20: A [illegible] **ace damage.**

7.2.2 FastSet DOT Mix

Most of the FastSet DOT Mix patches only had minor cracking on the surface. Patches #52, 54, 56, 57, 59, 63, and 64 all had low severity transverse cracking. Patches #56, 63, and 64 also had low severity longitudinal cracking. Patches #58, 60, 66, 67, 68, and 69 had low severity block cracking. Patch #69 also had a longitudinal blowout. Patch #64 also had moderate severity cracking along an existing crack in the surrounding pavement. Patch #65 had transverse and longitudinal spalling that met to form a blowout. Figures 21 and 22 show the deterioration of patch #64 and 65, respectively.

Figure 22: Patch #65 contains a blowout.

7.2.3 FlexSet

FlexSet patches #8, 9, and 11 had low severity durability cracking (d-cracking). Patch #8 also had minor spalling in one corner and portions of pavement missing from the right and left side of the patch, which is shown in Figure 23. Patch

#4 also had longitudinal joint spalling. Patch #5 had low severity corner cracking. Patches #2, 9, and 11 also had moderate severity durability cracking along the joint separating the patch from the MG Krete patch directly next to it. Patch #2 is shown in Figure 24.

Figure 23: This FlexSet patch shows pavement missing next to it.

Figure 24: Patch #2, which is on a bridge deck directly next to a failed MG Krete patch, shows durability cracking.

7.2.4 MG Krete

Patch #1 of MG Krete required a full depth patch repair after it blew out completely on a bridge deck. Patch #6 had low severity longitudinal cracking going through the length of the patch, which is shown in Figure 25. Patch #7 had low severity block cracking. Patch #13 had low severity map cracking. Patch D1 had low severity transverse cracking.

7.2.5 RepCon 928

RepCon 928 patch #70 had low severity cracking running longitudinally through the patch and small spalls at the top and bottom of the crack. Patches #71, 72, 73, 74, 75, and 84 had low severity transverse cracking. Patches #78 and 81 had low severity map cracking. Patch #80 and D5 had low severity map cracking. Patch #75 also had moderate severity longitudinal joint spalling. Patch #76 had spalling along a crack fault line, as shown in Figure 26. Patch D3 had a left corner blowout and is shown in Figure 14. Patch D4 had joint transverse spalling on the bottom right corner. Figure 15 shows patch D4. Half of patch D5 failed, requiring Durapatch to be placed on the right half of the patch, and can be seen in Figure 16.

7.2.6 SR-2000

Many of the SR-2000 patches did not pass the delamination testing. Patch #15 and 17 had bottom right corner cracking and blowouts. Figure 27 shows the cracking and blowout of patch #15. Patch #16 had bottom right corner cracking. Patch #24 had spalls present. Patch #29 had low severity transverse cracking. Patch #31 had surface pitting on the top right.

7.3 Acoustic Concrete Tester Results

The Acoustic Concrete Tester was used to estimate the normal thickness of the patch materials. The depth of the patch material was not exactly what the research team was trying to determine; rather, the ACT was used to assess whether or not the patch material was bonding well to the substrate. The typical thickness of highway pavements range from 9 inches (229 mm) to 12 inches (305 mm). This was used as a baseline approximation when analyzing the ACT data.

Figure 28 below shows the 2015 ACT data for Delpatch. The majority of the data falls under the 12 to 15 inch and greater than 15 inch (381 mm) thickness. Only one patch reading was within the desired 9 to 12 inch range. This may be because the ACT is not meant to be used on asphalt or flexible pavements; Delpatch is an elastomeric concrete. Figure 29 shows the 2016 ACT data for Delpatch. The majority of the data falls under the 9 to 12 inch range. However, a good amount of data falls under the less than 9 inch and 12 to 15 inch range. As mentioned before, this discrepancy may be because Delpatch is an elastomeric material.

Figure 30 shows the 2015 ACT data for Fast Set DOT Mix. The majority of the data falls under the less than 9-inch range. This could dictate that there is possible debonding or air voids or cracks beneath the surface of the patch. Figure 31 shows the 2016 ACT data for Fast Set DOT Mix. The majority of the data falls under the 9 to 12 inch range, which is ideal.

Figure 32 shows the 2015 ACT data for FlexSet. Most of the data falls under the greater than 15 inch range, but there is still a large amount of data falling under the 9 to 12 inch range. FlexSet is a flexible repair material, which is why the data appears slightly skewed. Figure 33 shows the 2016 ACT data for FlexSet. Most of the data falls under the 9 to 12 inch range, but also under the 12 to 15 inch and greater than 15-inch range.

Figure 34 shows the 2015 ACT data for MG Krete. The majority of the data falls under the less than 9-inch range, while none of the data falls under the 9 to 12 inch range. This may be due to coupling issues with the black putty. Figure 35 shows the 2016 ACT data for MG Krete. The majority of the data falls under the 9 to 12 inch range.

Figure 36 shows the 2015 ACT data for RepCon 928. The majority of the data falls under the less than 9-inch range. This could be because of coupling issues or possible air voids or cracks beneath the surface. Figure 37 shows the 2016 ACT data for RepCon 928. The majority of the data falls under the 9 to 12 inch range, but a sizable amount also falls under the less than 9-inch range and 12 to 15 inch range.

Figure 38 shows the 2015 ACT data for SR-2000. The majority of the data falls under the less than 9-inch range, followed closely by the 9 to 12 inch range and the 12 to 15 inch range. Figure 39 shows the 2016 data for SR-2000. The majority of the data falls under the less than 9-inch range. This is most likely due to the flexibility of SR-2000.

It is important to note that the two testing dates had very different weather conditions and ambient temperatures. The June 2015 testing was hot and sunny, while the March 2016 testing was cooler and overcast. The ACT transducers require putty to ensure complete contact with the pavement; the black putty has greater coupling properties compared to the white putty. However, the black putty had a tendency to soften and leave a residue on the pavement in hot, humid weather. The white putty performs better than the black putty in hot weather. The research team did not have access to the white putty during either testing date and encountered coupling issues with the ACT in June. The black putty had to be constantly removed and replaced with fresh putty. Also, because the putty had become so soft, small debris and particles stuck to the transducers. The black putty became coated very quickly and frequently, which could decrease the coupling or decrease the resonant frequency sharpness. It is recommended to use the white putty during hot and humid weather to increase coupling and performance.

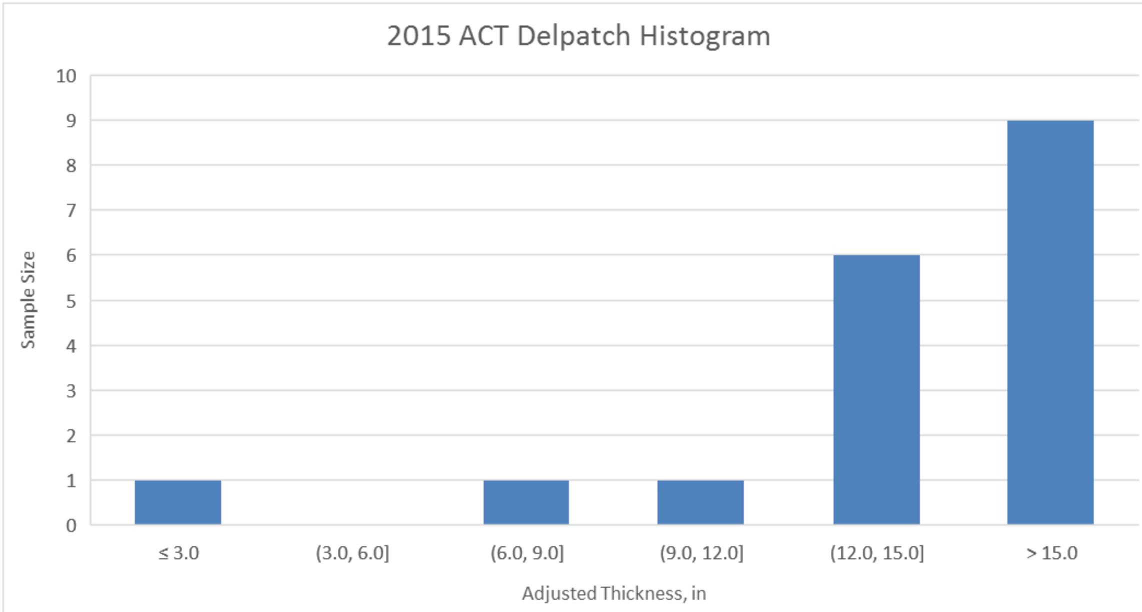

Figure 28: 2015 ACT results for Delpatch.

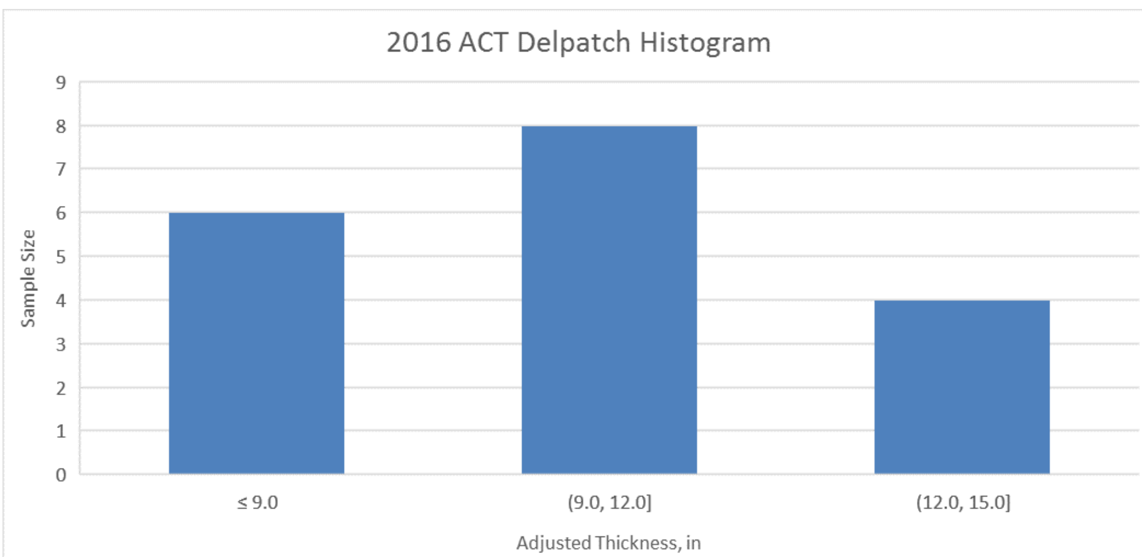

Figure 29: 2016 ACT results for Delpatch.

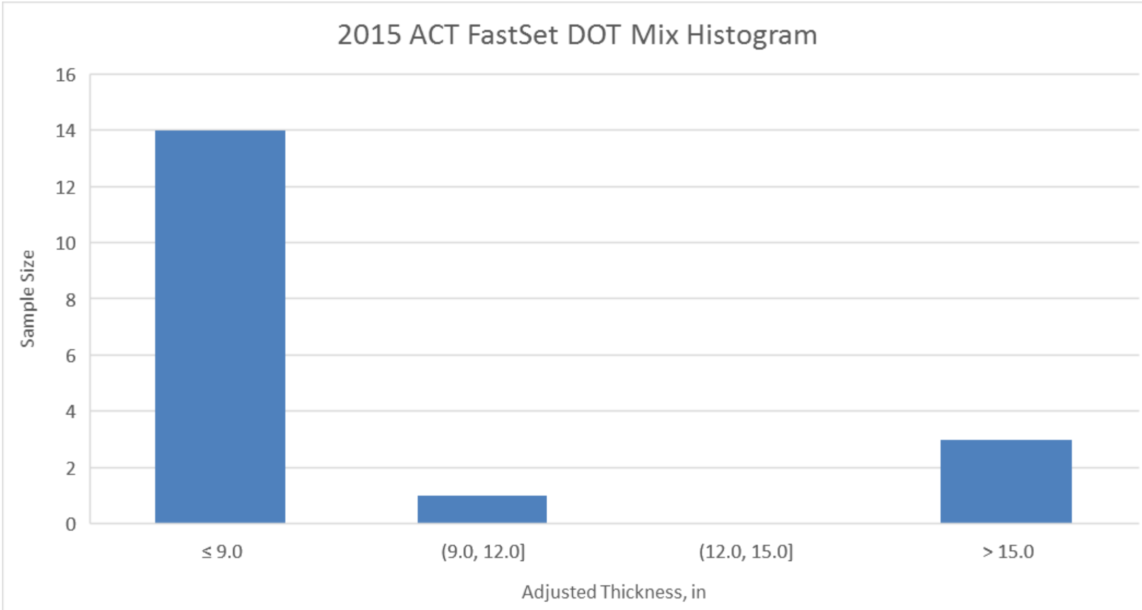

Figure 30: 2015 ACT results for Fast Set DOT Mix.

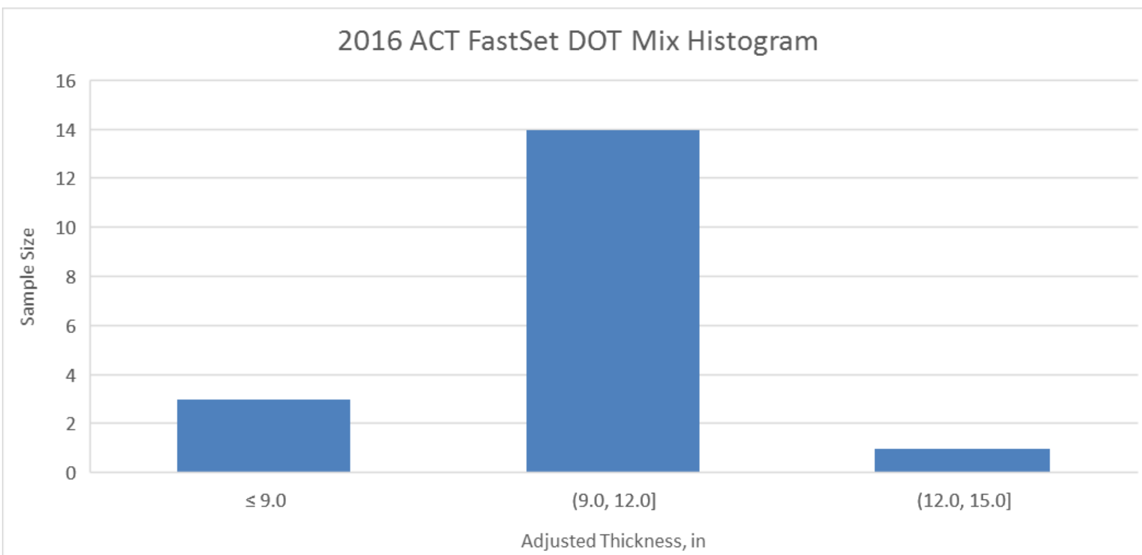

Figure 31: 2016 ACT results for Fast Set DOT Mix.

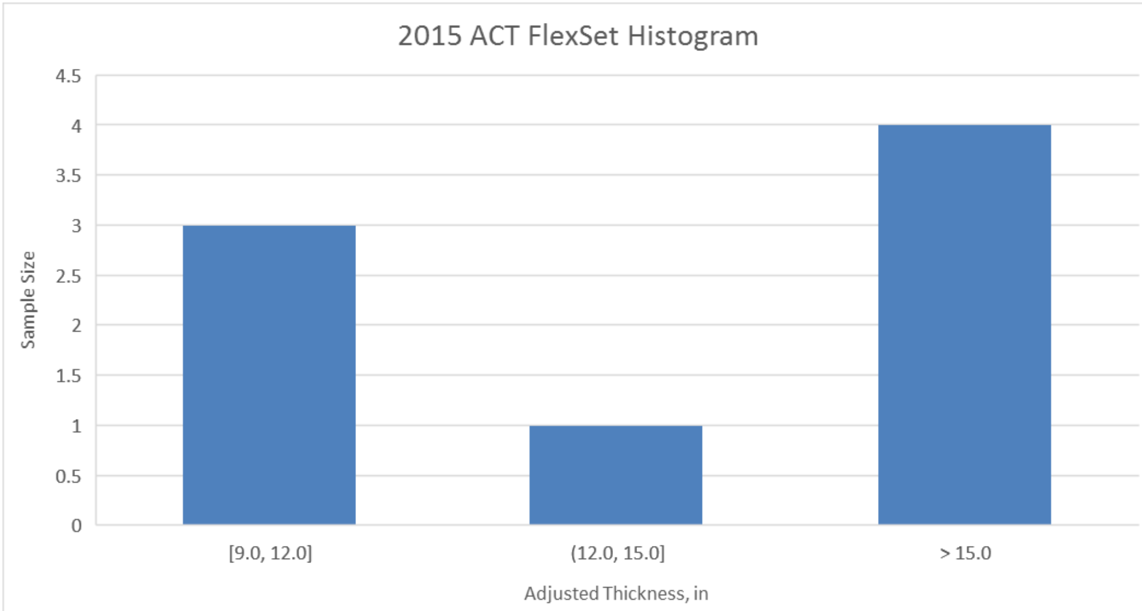

Figure 32: 2015 ACT results for FlexSet.

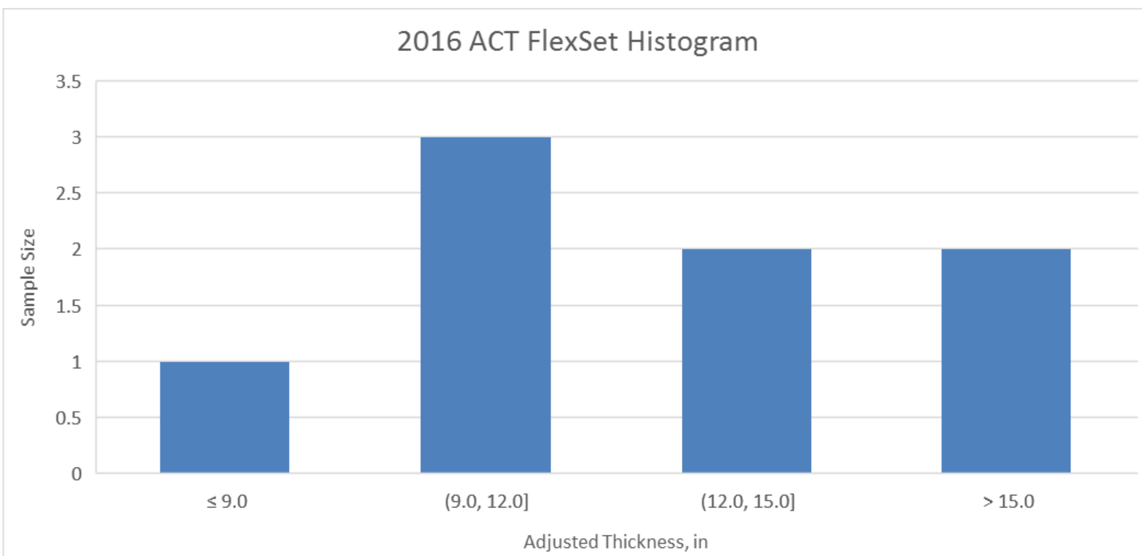

Figure 33: 2016 ACT results for FlexSet.

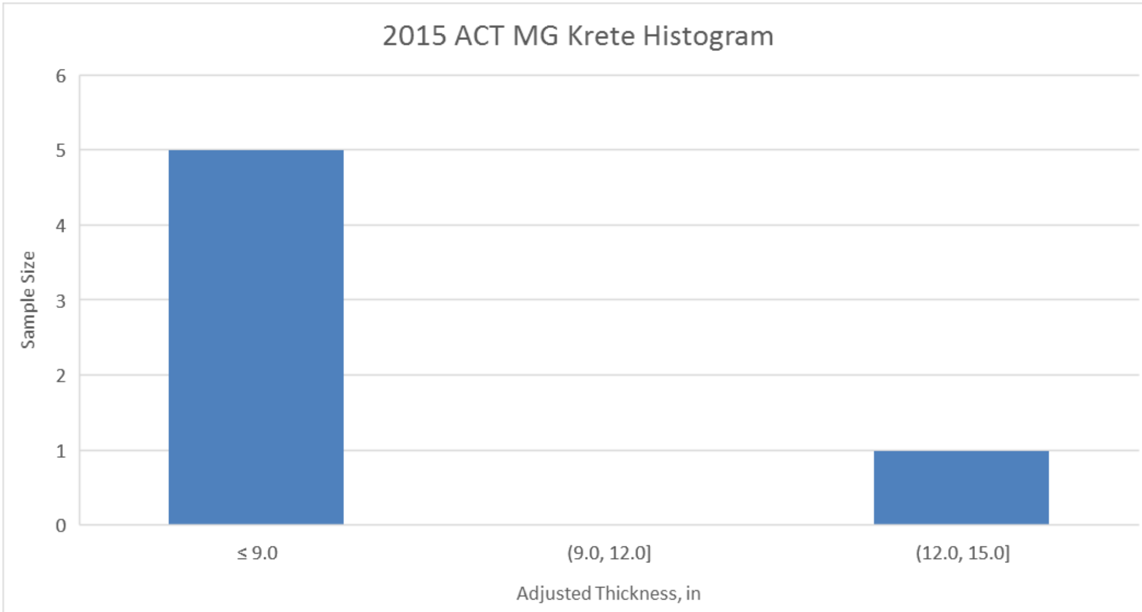

Figure 34: 2015 ACT results for MG Krete.

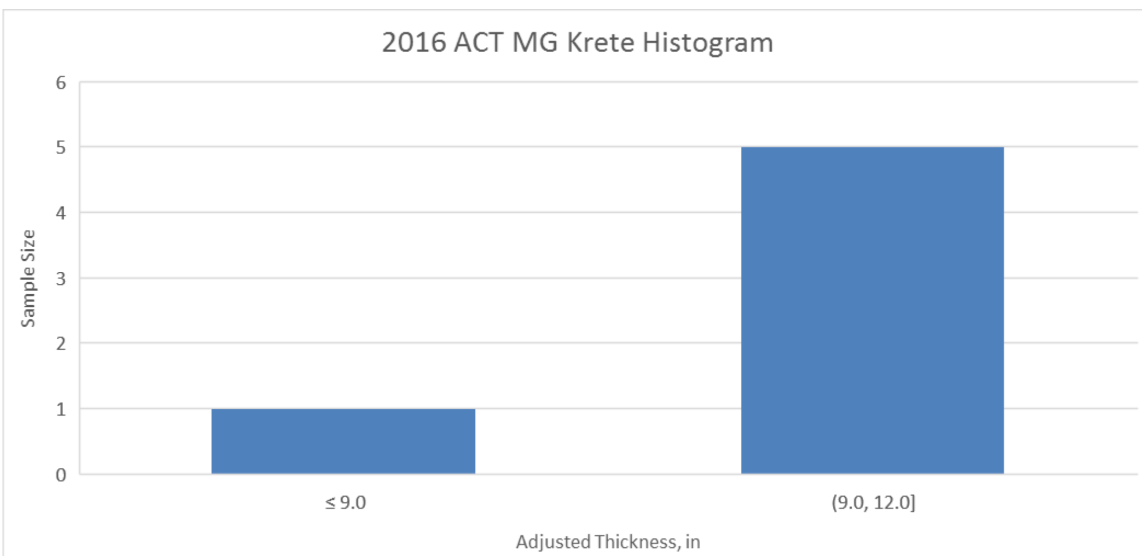

Figure 35: 2016 ACT results for MG Krete.

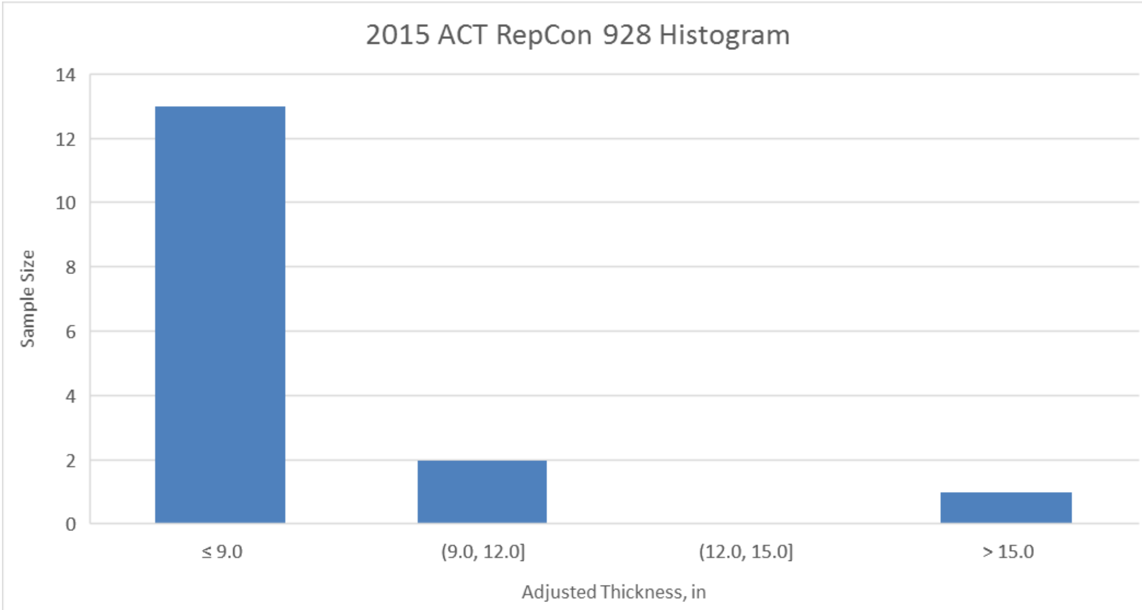

Figure 36: 2015 ACT results for RepCon 928.

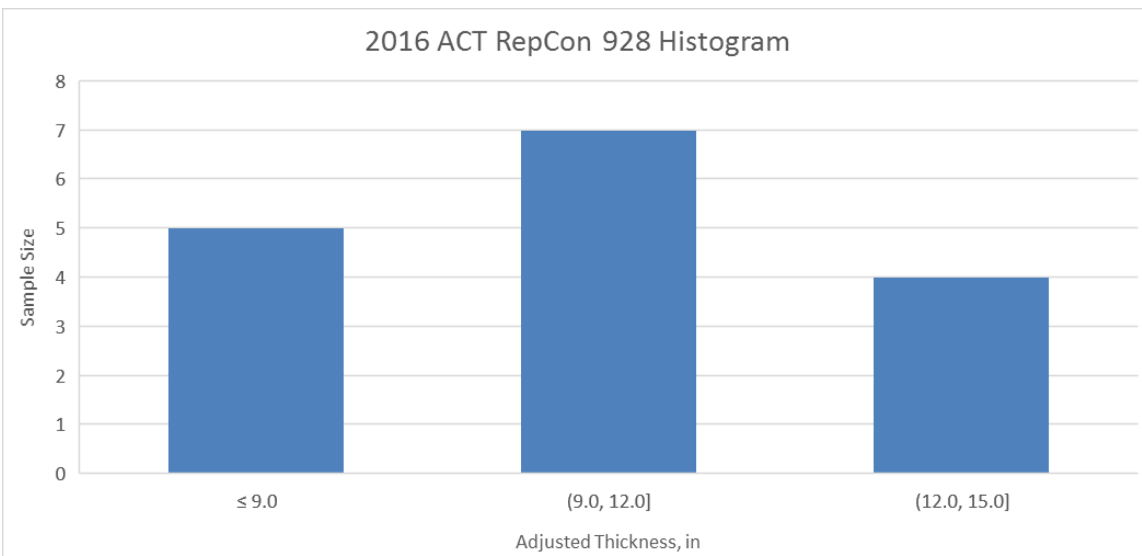

Figure 37: 2016 ACT results for RepCon 928.

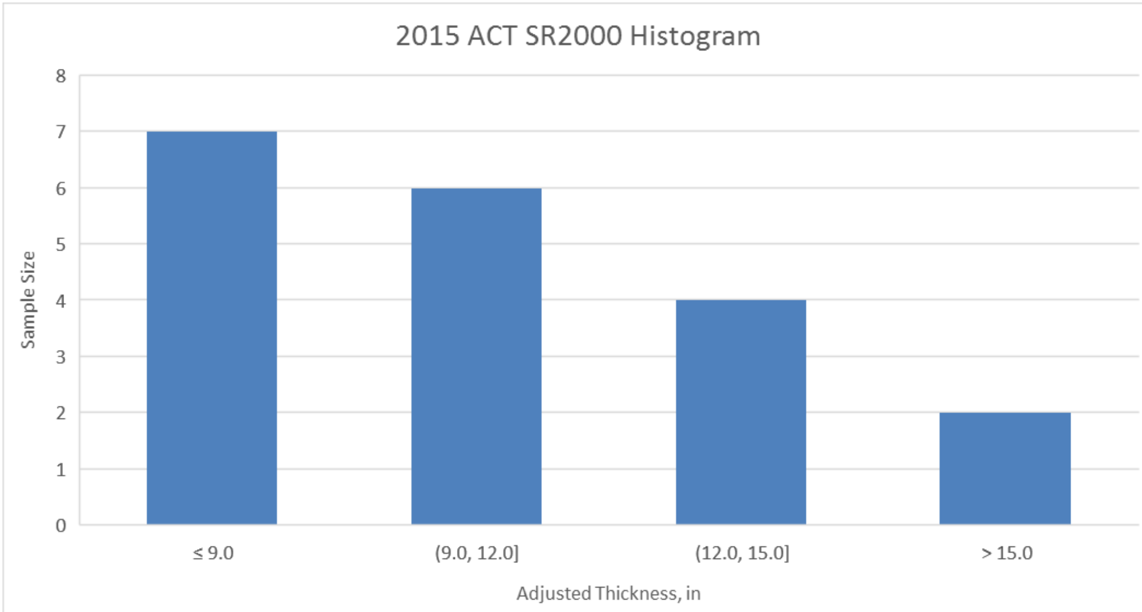

Figure 38: 2015 ACT results for SR-2000.

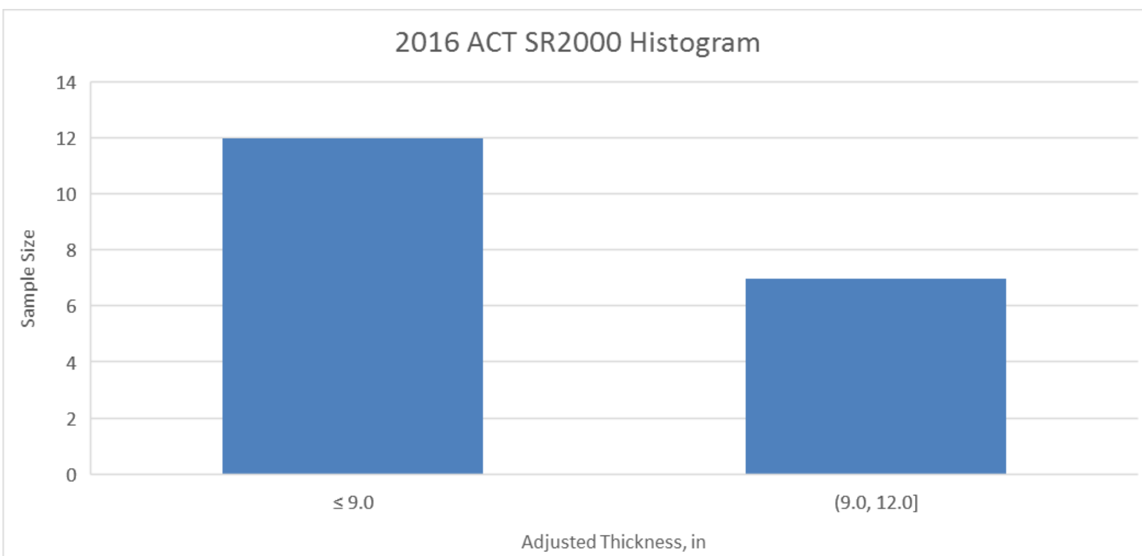

Figure 39: 2016 ACT results for SR-2000.

7.4 Rebound Hammer Results

The rebound hammer was used to test the different patch materials during this study. The research team tested the patches in June 2015 and March 2016. Five additional patches were installed in July 2015, which were tested with the other 85 in March 2016.

The rebound hammer measures the distance that the hammer rebounds; this distance correlates to a rebound number. This rebound number then correlates to an estimated strength of the patch material. Following the procedure listed in ACI C805/C805M – 13, the rebound hammer must be tested perpendicular to the testing surface. Ten readings should be taken with no less than 1 inch (25 mm) between impact points.

When analyzing the rebound hammer data, the average of all ten readings should be averaged. Readings that are more than 6 units away from the average should be discarded. If no more than 2 readings were discarded, then the remaining readings should be averaged again. If more than 2 readings are more than 6 units away from the average of the ten readings, then the whole series is discarded (ACI C805/C805M – 13, 2013).

For the June 2015 testing, the majority of the data was not usable. There are many factors that affect the rebound hammer's accuracy: moisture content on the test surface, the type of finishing used on the surface, vertical distance from the bottom of concrete placement, and the depth of carbonation (ACI C805/C805M – 13, 2013).

For the March 2016 testing, each type of material yielded results. Delpatch had an average estimated strength of 1686 psi (12 MPa) and an average rebound number of 35. FastSet DOT Mix had an average estimated strength of 3183 psi (22 MPa) and an average rebound number of 47. FlexSet had an average estimated strength of 2069 psi (14 MPa) and an average rebound number of 39. MG Krete had an average estimated strength of 2960 psi (20 MPa) and an average rebound number of 46. RepCon 928 had an average estimated strength of 5068 psi (35 MPa) and an average rebound number of 58. SR-2000 had an average estimated strength of 4582 psi (32 MPa) and an average rebound number of 54. These results are tabulated below in Table 6.

Month/ Year	Material	Compressive Strength, psi	Rebound Number
Mar-16	Delpatch	1686	35
Mar-16	Fast Set DOT Mix	3183	47
Mar-16	FlexSet	2069	39
Mar-16	MG Krete	2960	46
Mar-16	RepCon 928	5068	58
Mar-16	SR-2000	4582	54

Table 6: March 2016 testing results from the rebound hammer.

Delpatch and FlexSet had the lowest estimated strengths out of all six materials. This is most likely due to both being polymer concretes; the rebound hammer is not intended for this type of pavement, as it does not yield accurate results.

Also during the March 2016 testing, the five new patches were tested using the rebound hammer. The results are tabulated below in Table 7 and 8.

Month/ Year	Patch No.	Material	Compressive Strength, psi	Rebound Number
Mar-16	D1	MG Krete	2350	41
Mar-16	D2	MG Krete	5350	59

Table 7: March 2016 results for patches D1 and D2.

Month/ Year	Patch No.	Material	Compressive Strength, psi	Rebound Number
Mar-16	D3	RepCon 928	2500	41
Mar-16	D4	RepCon 928	4800	57
Mar-16	D5	RepCon 928	4600	55

Table 8: March 2016 results for patches D3, D4, and D5.

Table 7 shows the two new patches D1 and D2, which were made of MG Krete. There is a large discrepancy in the estimated strength. This could indicate that there is cracking or deterioration on or below the surface of patch D1, as it a strength that is almost half that of D2. Table 8 shows the other three new patches D3, D4, and D5, which were made of RepCon 928. D3 shows a much lower strength than D4 and D5, which could also indicate that the patch has damage or is failing. The strength of the patch material should be similar to, or greater than, the surround pavement strength. In this case, D1 and D3 have lower strength than that of its sister patches.

CHAPTER VIII

CONCLUSION AND RECOMMENDATIONS

8.1 Summary

The research team conducted visual inspections of the patches installed in 2014, installed five new patches in June 2015, and tested all existing patches in the field with the ACT and rebound hammer. Building on Andrew Lesak's thesis, the team was able to monitor the patches that are most likely to fail or require maintenance in the future; two patches on two different bridge decks have already failed (Patch #1 and D5). In both cases, it appears that the substrate failed, as opposed to the patch material. Both bridge decks have multiple patches scattered about, which indicates that the bridge decks need rehabilitation. This is something that the patch materials cannot repair; GRE-35-0963L is scheduled for extensive repairs in Spring 2016.

The objective of this thesis was to find which of the six patch materials installed in the field performed the best after multiple freeze-thaw cycles. Based on the information found in this thesis, paired with visual inspections and nondestructive testing, the research team was able to identify which materials performed well enough to consider for future patching use.

The six patch materials are as follows: Delpatch, FastSet DOT Mix, FlexSet, MG Krete, RepCon 928, and SR-2000. SR-2000 was eliminated from selection as most of the patches had delamination issues and half of the patches were in poor condition, with multiple cracks. The ACT results for SR-2000 were inconclusive, since it is a flexible resin. The average estimated strength of the SR-2000 patches was 4600 psi, which was the second highest out of all six patch materials.

FlexSet also was eliminated because of its high cost of $235 per cubic foot and because half of the cracked patches were in poor condition. The average estimated strength was low at 2100 psi, which determined that FlexSet might not be a desirable material to use in freeze-thaw climates.

MG Krete had a lower average estimated strength of 3000 psi, compared to FastSet DOT Mix's 3200 psi. MG Krete also set very quickly, which caused problems finishing and tining the patches. MG Krete was also more expensive, at $122.22 per cubic foot.

FastSet DOT Mix had the lowest cost of all six materials at $11.32 per cubic foot. However, approximately 78% of the patches had some form of cracking or surface damage. FastSet had the highest percentage of cracked patches, which eliminated it from being chosen as the best performing patch material.

While all 18 of the Delpatch patches performed well in the field, with no cracking or surface damage, the product was noted to be extremely difficult to work with and was sticky to remove from the mixer. Delpatch is also the second most expensive material at $232.43 per cubic foot.

RepCon 928 had the highest average estimated strength of 5100 psi and only costs $57.36 per cubic foot, which is the second lowest cost of all six patching materials. RepCon 928 was also the most workable product and was easy to clean out of the mixers and did not require any primer or special tools to mix. Therefore, RepCon 928 was the highest performing patch material.

8.2 Conclusion

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

- Documenting the installation and field-testing of the bridge deck, asphalt pavement, and concrete pavement patches
- Reporting the installation and field performance of existing patches, as well as the patches installed during this study
- Performing visual patch inspections and field-testing following patch installation

The purpose of these objectives was to determine which repair materials performed well in the field. The field-testing was performed for all repair materials and each patch was visually inspected multiple times during this study. The data and information listed in this thesis, as well as the prior one, give insight into the performance of each repair material.

Patch material failures can be attributed to the locations they are placed; the two bridge deck patch failures discussed in this thesis can most likely be attributed to substrate failure. Future repair material failures will most likely be due to cold joints that formed when each layer of repair material set before the next was placed. Other failures may be caused by: deteriorating pavement surrounding the patch, patches placed on or near control joints or expansion joints, two different patch materials installed directly next to each other, and cracking and failure near patches.

8.3 Future Research

Future research for this study involves continually monitoring the existing patches for signs of cracking, debonding, delamination, or failure. Visual inspections should occur routinely, and the repair areas that show distress to the patches and pavement surrounding should be under constant watch for failure. The patch materials should undergo some form of nondestructive testing to determine the soundness and uniformity of the patches after each freeze-thaw cycle.

REFERENCES

"1260 MG Krete." *ImcoTechnologies.com*. Imco Technologies, Inc., 2012. Web. 16 Apr. 2016.

Amini, Kamran, "Laboratory Testing of High Performance Repair Materials for Pavements and Bridge Decks," MSCE Thesis, Cleveland State University, May 2015.

Baldwin, N. J. R., and E. S. King. *Field Studies of the Effectiveness of Concrete Repairs*. 2003. Phase 1 Report. United Kingdom.

Barde, Amit, Swathi Parameswaran, Todd Chariton, Jason Weiss, Menashi D. Cohen, and Scott Newbolds, P.E. *Evaluation of Rapid Setting Cement-Based Materials for Patching and Repair*. Oct. 2006. Indiana Department of Transportation Final Report. Indiana, West Lafayette.

Cervo, Nicholas M., and Andrea J. Schokker. *Bridge Deck Patching Materials*. June 2008. Pennsylvania Department of Transportation Final Report. Pennsylvania, University Park.

Construction Administration Manual of Procedures. Columbus, OH: State of Ohio, Dept. of Transportation, 2013. Print.

Construction and Material Specifications. Columbus, OH: State of Ohio, Dept. of Transportation, 2013. Print.

"Delpatch™ Elastomeric Concrete." *The D.S. Brown Company*. D.S. Brown, 2016. Web. 27 May 2016.

"FastSet DOT Mix and FastSet DOT Mix and FastSet DOT Mix - Extended." *Quikrete.com*. The Quikrete Companies, 2012. Web. 29 May 2016.

"FlexSet for Concrete Repair." *FlexSet Concrete Repair*. Roklin Systems Inc., 2013. Web. 30 May 2016.

Frentress, Daniel P., and Dale Harrington. *Guide for Partial-depth Repair of Concrete Pavements*. Ames: Iowa State U Institute for Transportation, 2012. Print.

Inspection Instruments, Inc. *Acoustic Concrete Tester ACT User's Manual*. Feb. 2008. User Manual. Ohio, Cleveland.

"L&M Construction Chemicals LATICRETE." *DURAPATCH INDUSTRIAL ™ Rapid Strength, Flowable Repair Mortar with Extended Work Time*. LATICRETE International, Inc., 5 May 2008. Web. 18 Apr. 2016.

Lesak, Andrew, "Installation and Field Testing of High Performance Repair Materials for Pavements and Bridge Decks," MSCE Thesis, Cleveland State University, December 2014.

Miller, John S., and William Y. Bellinger. *Distress Identification Manual for the Long-Term Pavement Performance Program*. McLean: U.S. Dept. of Transportation, Federal Highway Administration, 2003. Print.

Nazzal, Munir D., Sang-Soo Kim, and Ala R. Abbas. *Evaluation of Winter Pothole Patching Methods*. Jan. 2014. Final Report. Ohio, Athens.

"Profile Publications Story - Southeast Resins Develops SR-2000 Concrete, Asphalt Polyester Repair System." *Southeast Resins Develops SR-2000 Concrete, Asphalt Polyester Repair System*. Superintendent's Profile, 1 July 2003. Web. 30 May 2016.

Sommerville, Alice, "Selection of High Performance Repair Materials for Pavements and Bridge Decks," MSCE Thesis, Cleveland State University, May 2014.

"Technical Data: RepCon 928 FS." *SpecChemLLC.com*. SpecChem, May 2015. Web. 16 Apr. 2016.

American Concrete Institute (ACI) Documents

ACI 228.2R-13 Nondestructive Test Methods for Evaluation of Concrete in Structures, (2013).

American Standards for Testing and Materials (ASTM) Documents

American Society for Testing and Materials. (2015). ASTM C1383 Standard Test Method for Measuring the P-wave Speed and the Thickness of Concrete Plates Using the Impact-Echo Method. West Conshohocken, Pennsylvania: ASTM.