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Effects of Concrete Moisture on Polymer Overlay Bond Over New Concrete

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Epoxy polymer overlays have been used for decades on existing bridge decks to protect the deck and extend its service life. The polymer overlay's ability to seal a bridge deck is now being specified for new construction. Questions exist about the amount of drying time needed to achieve an acceptable concrete moisture content to ensure an adequate bond to the polymer overlay. The 2007 Kansas Department of Transportation (KDOT) specifications for new bridge decks call for a 14-day wet curing period followed by 21 days of drying. If not enough drying is provided, the moisture within the concrete can form water vapor pressure at the overlay interface and induce delamination. If too much drying time is provided, projects are delayed, which can increase the total project cost or even delay overlay placement until the next spring.

A testing procedure was developed to simulate a bridge deck in order to test the concrete moisture content and bonding strength of the overlay. Concrete slabs were cast to test typical concrete and curing conditions for a new bridge deck. Three concrete mixtures were tested to see what effect the water-cement ratio and the addition of fly ash might have on the overlay bond strength. Wet curing occurred at three different temperatures (40°F, 73°F, and 100°F) to see if temperature played a part in the bond strength as well. The concrete was then allowed to dry for 3, 7, 14, or 21 days. Five epoxy-polymer overlay systems that had been preapproved by KDOT were each used in conjunction with the previously mentioned concrete and curing conditions.

After this, the slabs were setup to perform pull-off tests to test the tensile rupture strength. The concrete slabs with the different epoxy overlays were heated to 122-125°F to replicate summer bridge deck temperatures. Half of the pull-off tests were performed when the slabs were heated and half were performed once the slabs had cooled back down to 73°F ± 5°F.

Results from the pull-off tests as well as results from a moisture meter taken on the concrete prior to the overlay placement were compared and analyzed. Testing conditions were compared with each other to see which had a larger effect on the epoxy polymer overlay's bond strength. The results showed that concrete bridge deck polymer overlays could be placed sooner than 21 days after concrete placement and still have an adequate bond.

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Final Report

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PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

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Abstract

Epoxy polymer overlays have been used for decades on existing bridge decks to protect the deck and extend its service life. The polymer overlay's ability to seal a bridge deck is now being specified for new construction. Questions exist about the amount of drying time needed to achieve an acceptable concrete moisture content to ensure an adequate bond to the polymer overlay. The 2007 Kansas Department of Transportation (KDOT) specifications for new bridge decks call for a 14-day wet curing period followed by 21 days of drying (KDOT, 2007). If not enough drying is provided, the moisture within the concrete can form water vapor pressure at the overlay interface and induce delamination. If too much drying time is provided, projects are delayed, which can increase the total project cost or even delay overlay placement until the next spring.

A testing procedure was developed to simulate a bridge deck in order to test the concrete moisture content and bonding strength of the overlay. Concrete slabs were cast to test typical concrete and curing conditions for a new bridge deck. Three concrete mixtures were tested to see what effect the water-cement ratio and the addition of fly ash might have on the overlay bond strength. Wet curing occurred at three different temperatures (40°F, 73°F, and 100°F) to see if temperature played a part in the bond strength as well. The concrete was then allowed to dry for 3, 7, 14, or 21 days. Five epoxy-polymer overlay systems that had been preapproved by KDOT were each used in conjunction with the previously mentioned concrete and curing conditions.

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Results from the pull-off tests as well as results from a moisture meter taken on the concrete prior to the overlay placement were compared and analyzed. Testing conditions were compared with each other to see which had a larger effect on the epoxy polymer overlay's bond strength. The results showed that concrete bridge deck polymer overlays could be placed sooner than 21 days after concrete placement and still have an adequate bond.

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Due to file size, Appendices A to I are available in a separate file located at:

http://ksdot1.ksdot.org/burmatrres/kdotlib2.asp

or by contacting the KDOT Library at library@ksdot.org or 785-291-3463.

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Chapter 1: Introduction

1.1 Research Background

Epoxy-polymer overlays are used on concrete bridge decks to protect the deck and extend its service life. The epoxy consists of two components: a resin and a binder. Mixing these two components produces a thermosetting resin that is moisture tolerant (Potter, 1975). Combining the epoxy with a flint aggregate provides an overlay system that can seal and protect a bridge deck while creating a skid-resistant driving surface. Epoxy overlays are typically only 3/8 to 1/2 inches thick (Sika Corp., 2011).

The Kansas Department of Transportation (KDOT) has been using epoxy-polymer overlays on existing bridge decks since 1999 with great success (Meggers, 2009). Because of this effectiveness when placed on existing bridge decks, KDOT is investigating placing the epoxy-polymer overlay on new bridge decks.

1.2 Problem Statement

Placing the epoxy overlay on a new bridge deck creates a question about the acceptable moisture content in the concrete to allow for an adequate bond to the bridge deck. If the overlay is placed too early, water vapor pressure can form at the overlay interface and induce delamination. Current KDOT specifications call for 14 days of wet cure followed by 21 days of drying before placing an epoxy overlay on a new bridge deck (KDOT, 2007). Having too much drying time delays projects and increases costs. For bridges constructed toward the end of summer, overlay placement can be delayed until the next spring due to low temperatures. The bridge deck is then exposed to water and chlorides over its first winter cycle. Research is needed to determine acceptable moisture content and drying time of the bridge deck prior to placement of an epoxy overlay on new bridge decks.

1.3 Research Objectives

The research objectives of this study were as follows:

- Determine minimum drying times required after new concrete bridge decks are placed and wet cured in order to provide minimum bond strength required to prevent delamination.
- Determine if concrete moisture content meters could be used to determine if concrete bridge decks are dry enough for polymer overlays to be placed.

Chapter 2: Literature Review

2.1 Introduction

Bridge decks comprised of concrete and reinforcing steel support traffic loads and provide driving surfaces. From the moment bridge decks are opened to traffic, they are exposed to traffic loads, water, chlorides, and abrasion, leading to cracking which allows water and chlorides to enter the deck and contact the steel. Consequently, the steel corrodes and section area is lost, decreasing the strength capacity of the bridge. Therefore, initial bridge deck protection is crucial in order to increase the life span of a bridge.

2.1.1 Bridge Deck Protection

All bridge decks eventually experience accelerated deterioration, leading to mandatory full deck replacement; placement of an overlay system, however, can postpone this costly procedure. Overlay systems, such as concrete overlays, polymer-modified asphaltic overlays, and thin polymer overlays, prevent chlorides from entering the bridge deck and provide an abrasive driving surface. Concrete overlays utilize portland cement as a base material, but additional materials, such as silica fume, latex, and short fibers, are added to provide desirable overlay characteristics, including higher compressive/tensile strength, lower permeability, or earlier strength development. Polymer modified asphaltic overlays combine polymer material with an asphalt binder in order to create a sealant layer. Thin polymer overlays consist of a polymer and an aggregate less than 1 inch thick (Frosch, Kreger, & Strandquist, 2013). Polymer overlay types include methyl methacrylate, polyester, and epoxy. Methyl methacrylate overlays are monomers that utilize the slurry method of placement, in which the monomer and aggregate are mixed to create a slurry before being placed on the deck. Epoxy overlays comprise a multiple layer system that utilizes epoxy and an aggregate spread over each layer. Epoxy overlays are discussed in detail in this report.

2.1.2 Epoxy Polymer Overlay

Epoxy overlays are typically comprised of a resin and a binder; mixing these two parts produces thermosetting resin well-suited for protecting a bridge deck (Potter, 1975). Adhesive properties of hardened resin have adequate strength to typically out-perform the tensile strength of a concrete bridge deck ranging from 500-600 psi (Reagan, 1992). Materials can be added to the epoxy to specialize it to provide properties desirable for specific bridges or projects, such as increased compressive strength, hardness, or thermal conductivity (Guthrie, Nelsen, & Ross, 2005).

Epoxy polymer overlays are advantageous for bridge deck protection. According to Frosch et al. (2013), epoxy allows for short installation time, proper bond to concrete, impermeability, crack bridging, good skid resistance, and little additional dead load. Installation times for epoxy overlays are relatively short, with curing requiring only 1.5 hours for the first course and 3 hours for the second course (at 80-84°F) before opening to traffic (Dayton Superior Corp., 2012). Epoxies can have excellent bond strengths that reach over 500 psi within 24 hours (Poly-Carb, Inc., 2011). Epoxies are moisture resistant before and after curing, resulting in a sealed bridge deck (Sika Corp., 2011). Multiple epoxy layers prevent imperfections in one layer from destroying the integrity of the whole overlay system, and waterproofing the bridge deck keeps all water and chlorides from entering, thus preserving the internal reinforcement. Epoxy overlays are great at bridging cracks up to 0.04 inches wide, due to their tensile strength and elongation properties, but should be filled with a resin prior to overlay placement for cracks wider than 0.04 inches (Fowler & Whitney, 2011). With the use of a hard aggregate, epoxy overlays provide a good skid-resistant driving surface for years. Epoxy overlays are also very thin, typically 3/8 to 1/2 inches thick, adding very little dead load to the structure (Sika Corp., 2011). Because epoxy overlays are so thin, no modifications to roadway clearance or approach slabs are required, thereby simplifying installation.

An epoxy overlay can protect a bridge deck for up to 20 years if properly placed and maintained, so care should be taken to properly prepare a deck for an epoxy overlay. The concrete surface is critical because it directly bonds with the epoxy. The surface should be free of moisture, roughened by shot-blasting, and free of solid or chemical debris. Dry, warm temperatures offer optimum curing conditions for the epoxy. Epoxy overlay application should be completed by an experienced crew supervised by the epoxy producer to ensure proper placement (Fowler & Whitney, 2011).

2.2 Failure Mechanisms

2.2.1 Causes of Failure

If failures occur in the epoxy overlay system, they typically happen during overlay construction (Fowler & Whitney, 2011). The areas that lead to failure in the epoxy overlay most often occur during surface preparation, proportioning, mixing, curing, or overlay finishing. Concrete repair and surface preparation are crucial to the concrete-epoxy bond, which is usually stronger than the concrete itself. Therefore, if the concrete is delaminated or spalled, then achieving a high bond strength to the deteriorated concrete does no good (Guthrie et al., 2005). Similarly, if foreign materials are on or within the concrete, the bond is unable to reach its full potential. For example, if chloride content in the concrete is reaching levels that can corrode steel, then the corroding steel will crack the concrete, causing delaminations in the overlay (Babaei & Hawkins, 1987). In the cases that have deteriorated concrete in any way, the damaged concrete must be removed and replaced. Repairs made with portland cement should be wet cured to decrease the amount of shrinkage and, furthermore, from debonding the polymer overlay as a result of the shrinkage (Fowler & Whitney, 2011). The bridge deck surface is related to the overlay bond because the rougher the bridge deck surface, the more area and friction is able to resist shear or tensile forces. According to the National Cooperative Highway Research Program (NCHRP), a surface roughness of 6 to 7 on the International Concrete Repair Institute (ICRI) roughness scale provides an adequate bonding surface (International Concrete Repair Institute, n.d.).

Materials used for the overlay can directly cause or aid in delaminations. Concrete and epoxy mechanical properties must be similar in order to avoid additional stresses caused from shrinkage or thermal expansion. Epoxies with a similar coefficient of thermal expansion to the concrete bridge deck prohibit additional shear stresses from forming at the bond due to differential expansion. Aggregate selected for the overlay must have good impact and abrasion resistance (Guthrie et al., 2005). An aggregate that breaks apart will decrease overlay abrasiveness and allow the overlay to break apart earlier. Clean aggregate is critical to keeping the aggregate from falling out of the overlay (Smith, 1991). Aggregate that has any dirt or foreign residues on it will be inhibited from bonding well to the overlay.

Many epoxy overlay systems use a 1:1 Part A to Part B ratio by volume for proportioning. Any variances from a 1:1 ratio by volume results in unused material, leading to soft spots and rutting in the overlay. Inadequate mixing of the epoxy, such as not fully blending the two parts or leaving unmixed epoxy on the sides of the mixing barrel will also result in the epoxy not having a perfect 1:1 ratio by volume. Epoxies, especially larger batches, should be mixed mechanically to avoid human error (Guthrie et al., 2005). Entraining air during mixing should be avoided since bubbles in the overlay allow direct access for chlorides through the overlay (Fowler & Whitney, 2011). A jiffy mixer or paddle attached to a low speed drill is recommended to keep entrained air to a minimum during mixing (Dayton Superior Corp., 2012). Overlay application should be conducted as specified in the epoxy product data sheet. The time needed to completely cure the epoxy will change with temperature variances (Poly-Carb, Inc., 2011).

Moisture on the deck surface or within the bridge deck can decrease the bond. Areas near drains or low spots must be closely monitored because they often retain moisture. Moisture within the concrete can rise to the bond interface and be unable to escape because the overlay is impermeable. The trapped moisture, when heated, creates high pressure with the water vapor, leading to delaminations (Guthrie et al., 2005).

Long-term damage can also lead to premature overlay failure. Ultraviolet radiation (UV) from the sun bears down on the overlay surface, causing epoxy molecules to break apart into smaller molecular structures that are more susceptible to erosion. However, the presence of aggregate protects the overlay from UV rays, and multiple layers prevent the damage from spreading too deep and ruining the water resistant seal on the bridge deck (Karbhari, Chin, & Reynaud, 2001). Prolonged structural strains cause cracks and stresses that the overlay is unable to resist, resulting in overlay failure (Stenko & Chawalwala, 2001).

2.2.2 Effects of Failure

Overlay failure types can be categorized into three groups: delamination of the overlay, increased porosity of the overlay, and loss of skid resistance (Guthrie et al., 2005). Delamination exposes the bridge deck, allowing chlorides to enter. Increased porosity creates cracks and holes by which chlorides can also penetrate the overlay. Loss of skid resistance eliminates friction required for adequate stopping distance for drivers, consequently increasing overlay hazards.

Delamination of the overlay from the bridge deck can result from inadequate overlay construction. A poorly roughened concrete surface is the primary contributing factor to delaminations. As noted previously, incorrect termination of the overlay at joints or failure to mix or cure the overlay correctly increases the potential for delamination. In addition, moisture at the bond interface weakens the overlay bond, especially during high temperatures during summer when moisture becomes water vapor. Drastic differences in thermal expansion or mechanical properties between the overlay and concrete can also lead to increased possibility of delamination (Nabar & Mendis, 1997). Delaminations can also repeatedly occur just below the concrete surface when the concrete is weaker than the bond. Figure 2.1 shows cores with concrete failures just below the concrete surface.

Figure 2.1: Failures in the Concrete

Increased porosity of the polymer overlay can cause multiple types of overlay failures because water and chlorides are granted immediate access to the bridge deck. Cracks can lead to a direct path through the overlay. Nabar and Mendis (1997) noted that cracks in the concrete often reflect up through the overlay. In a bridge study by Carter (1993) shown in NCHRP, a repaired bridge had 2,000 ft of flexural cracks and 20,000 ft of shrinkage cracks. Four years after overlay placement, approximately 325 ft of cracks were reflected up in the overlay. Another bridge with a lot of cracks prior to placing an overlay showed approximately 70% of the cracks reflecting up into the overlay.

Pitting is another type of porosity resulting from air bubbles entrained during mixing of the epoxy. Pits are pin-size to quarter-inch holes in the overlay that are present during overlay placement or form due to the environment (Harper, 2007). A pit can span the entire depth of the overlay layer it is present in. During Harper's investigation, it was expected that pits would not line up between multiple layers of epoxy since the probability was too low. If the pits did line up though, they would provide a funnel by which water and chlorides could enter the deck and corrode the steel. In a study by the Missouri Department of Transportation, 62 out of 98 bridges inspected demonstrated pitting with pits lining up between layers (Harper, 2007). Harper also found that increased temperatures and an increased number of freeze/thaw cycles resulted in additional pitting.

The third overlay failure type occurs in the abrasive surface of the overlay (Nabar & Mendis, 1997). A loss of skid resistance results in an unsafe driving surface. Incorrect aggregate types and gradation, such as having aggregates that are too fine, do not provide a sufficiently rough and durable surface for driving on. Aggregates can popout if they are not clean when placed in the overlay because dust and dirt prevent a good bond from establishing between the epoxy and aggregates. UV rays can also deteriorate the abrasive surface of the overlay over time.

2.3 Surveys

In this study, a survey of state Departments of Transportation (DOTs) was conducted to determine polymer overlay usage on newly placed concrete bridge decks. If a polymer overlay had been placed prior to opening the deck to traffic, questions then pertained to specifications or procedure changes. Responses were collected from 18 state DOTs, and a complete listing of the responses is included in Appendix G. The following questions were included in the survey.

1. Have you placed a polymer overlay on a newly poured bridge deck before opening to traffic?
2. Were any additional procedures taken when pouring/curing the concrete to accommodate for the early placement of the polymer overlay and how were they established?
    i. Specifically, what minimum wet curing and time is required?
    ii. How much drying time after removing the wet curing is required before the polymer overlay can be placed?
    iii. Is the bridge deck moisture content required to be checked before placement? If so, what method is used and what values were acceptable?
3. Were any additional procedures taken when placing the polymer overlay compared to placing the overlay on an existing bridge?
4. After placing the polymer overlay on the new bridge deck, what causes of failure were observed?
    i. Can they be specifically attributed to the placement of the overlay on the new concrete?
    ii. If applicable, what life span of the overlay was observed?

Question 1 responses indicated that only a few DOTs have placed a polymer overlay on a bridge deck prior to opening the deck to traffic. Illinois and Texas had used polymer overlays on new bridge decks, but not by design. These overlay placements are most likely due to construction problems that called for the bridge deck to be sealed early in its life. New York State and Pennsylvania have used polymer overlays on new bridge decks after they have gone through one winter cycle, thereby allowing early cracking to occur. The overlay, then placed after the winter, would bridge over and fill the cracks. Utah and Wisconsin claimed to have used a polymer overlay prior to opening to traffic by design.

Responses to Questions 2 and 3 can be combined and summarized. Overall results indicated that polymer overlays are placed 28 days after bridge deck placement. Illinois uses 7 days for wet cure and 28 days after casting the deck. New York State specified the time was the same as the time required to reach required strength of the deck. Wisconsin uses 14 days for wet cure and 28 days after batching. Virginia allows 28 days after casting the deck and also applies a curing compound. If an earlier timeframe is necessary, a test patch can be constructed to see if an overlay would be plausible. If bond strength tests were over 250 psi and failed in the concrete, the overlay would be allowed. Utah requires 14 days minimum, but the manufacturer recommends 28 days.

For DOTs that place a polymer overlay on new bridge decks, moisture in the concrete was commonly checked. Illinois, Wisconsin, and Missouri use ASTM D4263 (2012) *Standard Test Method of Indicating Moisture in Concrete by the Plastic Sheet Method* to check moisture in the deck for a minimum of two hours. New York State requires that no precipitation has fallen on the bridge deck during the previous 24 hours before the test and that a moisture meter read bridge deck moisture at less than 5%. Wisconsin requires that the moisture content be less than 4.5% when read by a moisture meter. No additional special provisions for new bridge decks were found.

No information has been obtained regarding failures on new bridge decks, but the Virginia DOT anticipates an epoxy overlay life span of 15-25 years, depending on traffic.

2.3.1 Survey on Polymer Overlay Usage

A questionnaire survey of state DOTs was conducted by Guthrie et al. (2005) from Brigham Young University. The purpose of the survey was to determine polymer concrete usage on bridge decks in the U.S. The questionnaire received 20 responses from state DOTs.

Questionnaire results led to the following conclusions about polymer overlay usage as of 2005. A majority of state DOTs placed polymer overlays to provide a chloride barrier or a skid resistant wearing surface. Polymer overlays were placed on a bridge deck when significant cracking or deterioration occurred or when rehabilitation was scheduled. A few DOTs set scheduled times for overlay usage ranging from two years for a deck seal in Wisconsin to 25 years in Idaho. Furthermore, when asked to distinguish the determining factor of when to apply a surface treatment, 10 DOTs claimed crack density, five claimed chloride concentration, 12 claimed bridge deck age, and four claimed skid resistance. A crack density that is too high can refer to 10% of deck cracked in New Mexico, or if crack widths exceed 0.007 inches in South Carolina. Idaho, New Jersey, and Wisconsin claimed that they place a deck seal when chloride concentration reaches 2-3 lbs per cubic yard at the depth of the reinforcing steel. No information was gathered on bridge deck age or skid resistance factors. Primary surface treatments utilized by DOTs are as follows: 10 epoxy, four epoxy-urethane, one urethane, seven methacrylate, two silicone, and 12 answers returned as other. Construction specifications to achieve good bond included the following:

- Substrate preparation
- Equipment
- Overlay thickness (Epoxys 0.250 to 0.375 inches thick)
- Climatic factors
- Lane closure requirements
- Personnel expertise
- Manufacturer representation
- Compliance with laboratory tests
- Contractor demonstration of past performance and compatibility

Climatic factors refer to dry, warm bridge deck conditions, lack of moisture in the weather forecast, and utilization of ASTM D4263 (2012). The most common modes of failure for surface treatments were cracking (10 responses) and delamination (11 responses). Shrinkage cracking and lack of quality control were the primary causes for cracking, while poor quality concrete and inadequate surface preparation were the primary causes of delamination. Three DOTs reported zero responses for skid resistance failure and UV damage as failure causes. Most DOTs reported bi-annual inspections on bridges with polymer overlays (Guthrie et al., 2005).

2.4 Previous Testing

In this section, previous research and testing from three studies related to polymer overlay usage and bond strength are presented. First, Gama (1999) performed experimental tests by saturating the concrete with water in an attempt to induce failure at the concrete/overlay interface due to water vapor pressure. Second, Young, Durham, and Bindel (2011) performed pull-off tests on two epoxy overlay systems on current bridges. Lastly, Pantelides and Weber (2011) performed pull-off tests on precast slabs when the overlay was placed before and after the induction of initial cracking.

Gama (1999) performed a water vapor pressure test to determine whether pressures created by heating up the slab could delaminate a polymer overlay. Because polymer overlays are only 0.25-0.5 inches thick, the assumption was made that only minimal pressure would be needed to induce delamination. For this experiment, portland cement concrete slabs 0.5 m (19.7 inches) wide × 0.5 m (19.7 inches) long × 0.05 m (1.97 inches) deep were cast with a polymer overlay placed on the top surface of the slab. The slabs were then placed underwater so that the concrete was underwater but the overlay was above the water level. Insulation surrounded the slabs so water could not escape out of the sides of the slab, thus ensuring that the slabs remained saturated and in a worst-case scenario. To induce water vapor pressure, the slabs were placed under UV heat lamps (250W, 120V) to replicate sunlight. The lamps were situated so that internal concrete temperatures reached 50°C (122°F). Five samples were placed under heat lamps for two weeks, during which time surface temperatures reached 90°C (194°F) and overlay interface temperatures reached 48-73°C (118-163°F), depending on heat lamp exposure. Concrete temperatures reached 53°C (127°F) and the water reached 48°C (118°F).

Gama (1999) calculated theoretical pressures that would be created by his research. Modeling a thermodynamic closed system, he theorized a water vapor pressure of 11.7 kPa (1.69 psi) when fully saturated at 50°C (122°F). Based on these calculations, the pressure did not seem strong enough to cause delamination. Neither ultrasonic tests nor visual inspection demonstrated any failures.

Pull-off tests were performed both on slabs heated while surrounded by water and on unheated control slabs also surrounded by water. Average pull-off tests for heated slabs ranged from 3.54-3.82 MPa, while average pull-offs for control slabs ranged from 3.40-3.73 MPa. Both pull-off sets were completed on room temperature slabs, and all pull-offs resulted in concrete failure. Water vapor pressure did not negatively affect bond strength of the polymer overlay (Gama, 1999).

Young et al. (2011) performed pull-off tests on two bridges: one with a Safelane overlay and one with a Flexogrid overlay. The overlays were only one to two years old at the time of the tests, and each overlay system had two pull-offs at four locations along the bridge. Safelane averaged 370 psi with all failures located in the concrete. Flexogrid produced failures in the concrete, at the interface, and in the test adhesive. Failure in the test adhesive was the only test to not reach 250 psi. By leaving out the test adhesive failure, the pull-offs tests ranged from 340-520 psi. All tests were performed at night with low temperatures.

Pantelides and Weber (2011) performed pull-off tests after applying polymer overlay before and after initial cracks were induced on precast slabs. The first testing type (Type 1) used two precast concrete deck slabs sized 18 inches × 8 feet × 8.75 inches thick. These slabs were turned upside down to crack the specimens, similar to the cracking that occurs during the construction and early life of the structure. The two slabs were grouted together and an epoxy overlay was applied. The slabs were then cyclically loaded for five days while daily pull-off tests were performed. The second type of testing (Type 2) was similar to the first type, but in this set, overlay was placed on the precast panels prior to flipping and inducing cracks. After cracking, one additional layer of overlay was placed to splice together the two panels. Cyclic loading and testing then occurred in the same manner as in the Type 1 tests.

Five polymer overlay systems were tested, only one of which was an epoxy polymer overlay. Pull-off tests were conducted using a 2-inch core and drilling 3/8 inches into the concrete. A tensile force was applied until failure. Pull-offs from Type 1 tests resulted in average valid pull-off strength of 673 psi with five out of the six pull-off tests (83%) failing in the concrete. Type 2 tests resulted in an average valid pull-off strength of 530 psi with six out of eight (75%) failing in the concrete. Results indicate that cracking induced with the overlay already on the panels resulted in lower pull-off values than panels that were cracked prior to overlay placement (Pantelides & Weber, 2011).

2.4.1 KDOT Multi-Layer Polymer Concrete Overlay Specifications

The *Standard Specifications for State Road & Bridge Construction* (KDOT, 2007), Section 729 contains KDOT’s requirements for placing a multi-layer polymer concrete overlay. The specification includes information regarding the equipment needed, preparation of the concrete surface, placement of the overlay, and weather conditions that are acceptable. A copy of this Specification is shown in Appendix H.

The equipment required for hand application situations start with calibrated containers to portion out the epoxy accurately. The paddle used needs to be able to completely mix the epoxy resin and hardening agent. A notched squeegee should be used to spread out the epoxy evenly over the concrete surface. Any other additional tools needed to place the overlay according to the specifications should also be on hand (KDOT, 2007).

Surface preparation is crucial to ensuring adequate overlay bond to the concrete. On existing structures, any deteriorated concrete should be removed and replaced. Portland cement concrete patches require a minimum of 28 days between the repairs and overlay placement. New structures receiving a polymer overlay should be wet cured for 14 days and then allowed to dry for 21 days (KDOT, 2007).

Prior to placing the polymer overlay, the bridge deck needs to be properly prepared. The deck should be shot blasted or another approved form of blasting to provide a roughened surface and also to remove any contaminating materials. The roughened surface should meet the requirements for a surface preparation level of 6 to 7 on the ICRI roughness scale or meet ASTM E965 (2006) pavement macrotexture depth of 0.04 to 0.08 inches. Shot blasting the surface also removes any contamination or weak surface concrete. After shot blasting, the deck should be air blasted or vacuumed to remove all dirt, paint, oil, curing materials, or foreign materials from the surface (KDOT, 2007).

Special care should be taken so the deck does not get contaminated after shot blasting. The shot blast equipment or any other equipment that would produce dust should not be emptied or cleaned closer than 50 feet from the bridge deck. Rain should not contact the surface between the surface preparation and the overlay placement. The reasons specifications do not allow for the surface to be rained on prior to the overlay placement are that the rain could be carrying contaminates and the deck should not contain too much moisture. To check for moisture, tape a plastic sheet to the concrete surface for a minimum of two hours in accordance with ASTM D4263 (2012) to see if moisture accumulates on the plastic sheet. The first course should be placed within 24 hours of shot blasting to minimize contaminates on the bridge deck (KDOT, 2007).

Overlay placements should be conducted according to contract documents and the epoxy manufacturer's specifications. A manufacturer representative is to be present upon placement of overlay to ensure proper placement. The overlay should be placed in two separate courses. The first course is to contain no less than 0.22 gal/sq yd of epoxy and at least 10 lbs/sq yd of aggregate. The second course should be no less than 0.45 gal/sq yd of epoxy and a minimum of 14.5 lbs/sq yd of aggregate. Enough aggregate should be spread on top of the epoxy so that no epoxy goes uncovered. The bridge deck, epoxy, and aggregate should all maintain a temperature above 60°F at all times. The epoxy should be spread evenly by the notched squeegee. Within 10 minutes, the dry aggregate should be cast onto the epoxy. Curing times for both the first and second courses can be found in Table 2.1. Excess aggregate should be vacuumed or swept off the deck after the epoxy has hardened. The first course should never be opened to traffic. The second course will then be placed using the larger proportions and cured for a minimum of eight hours. The overlay should be placed continuously and within the time limits. Any sections of the overlay that are not adequate are to be removed and replaced (KDOT, 2007).

Weather limitations do not allow for polymer overlays to be placed prior to April 1 or after September 30. The bridge deck temperature should never exceed 100°F during placement of the overlay and the air temperature should not fall below 55°F during curing. The overlay should also not be placed if at any time the temperature causes the gel time to be less than 10 minutes (KDOT, 2007).

Table 2.1: Polymer Concrete Overlay Cure Times

Polymer Concrete Overlay Cure Times							
Course	Average Temperature of Overlay Components °F						
	55-59	60-64	65-69	70-74	75-79	80-85	85+
	Minimum Cure Time (hours)						
1	5	4	3	2.5	2	1.5	1
2	6.5	6.5	5	4	3	3	3

Source: KDOT, 2007, Section 729

Chapter 3: Materials

3.1 Experimental Setup

As previously stated, placing an epoxy-polymer overlay on a newly placed concrete bridge deck makes the epoxy overlay susceptible to delamination caused by water vapor pressure. Moisture content within new concrete bridge decks is much higher than the moisture content of the concrete on existing bridge decks. Different concrete mixtures and curing conditions can have different effects on the moisture content within the concrete and, furthermore, cause different bond strengths between the concrete and overlay. Several concrete mixes and curing conditions were selected to test their effects on the concrete moisture content and overlay bonding strength. The conditions to be tested included concrete mix, wet cure temperature, drying time, epoxy-polymer overlay system, and temperature at time of pull-off test.

Concrete mixes selected included a control mix, a low-cracking mix, and a mix containing fly ash. The control mixture contained a water-to-cementitious ratio (w/c) of 0.50, the low-cracking mix contained a w/c of 0.44, and the fly ash mix contained 25% Class F fly ash and had a w/c ratio of 0.50.

Wet curing of the slabs occurred at 100% relative humidity for 14 days (KDOT, 2007). To test wet cure temperature effects on moisture within concrete at testing, three wet cure temperatures spanning normal construction temperatures were selected: 40°F, 73°F, and 100°F.

Dry curing of the slabs occurred at 73°F and 50% relative humidity for all slabs. Drying times were set at 3, 7, 14, and 21 days after wet curing, thus providing total curing times of 17, 21, 28, and 35 days after concrete casting to overlay placement.

Overlay systems were selected from the five pre-approved epoxy overlay systems currently accepted by KDOT: E-Bond 526 (E-Bond Epoxies, n.d.), Pro-Poxy Type III DOT (Dayton Superior Corp., 2012), Flexolith (Euclid Chemical Co., n.d.), Sikadur 22 Lo Mod (Sika Corp., 2011), and Mark 154 (Poly-Carb, Inc., 2011).

Temperatures at the time of pull-off testing were established as room temperature (73°F ± 5°F) and a hot temperature (122-125°F one inch below concrete surface). The room temperature replicates temperatures during early morning summer hours, while the hot temperature replicates temperatures experienced in the bridge deck during the heat of a summer day. Pull-off tests were conducted according to ASTM C1583-13 (2013).

A test matrix can be obtained with a combination of these conditions. A slab matrix of 180 slabs are required with three concrete types, three wet cure temperatures, four drying times, and five overlay systems. Figure 3.1 shows this test matrix.

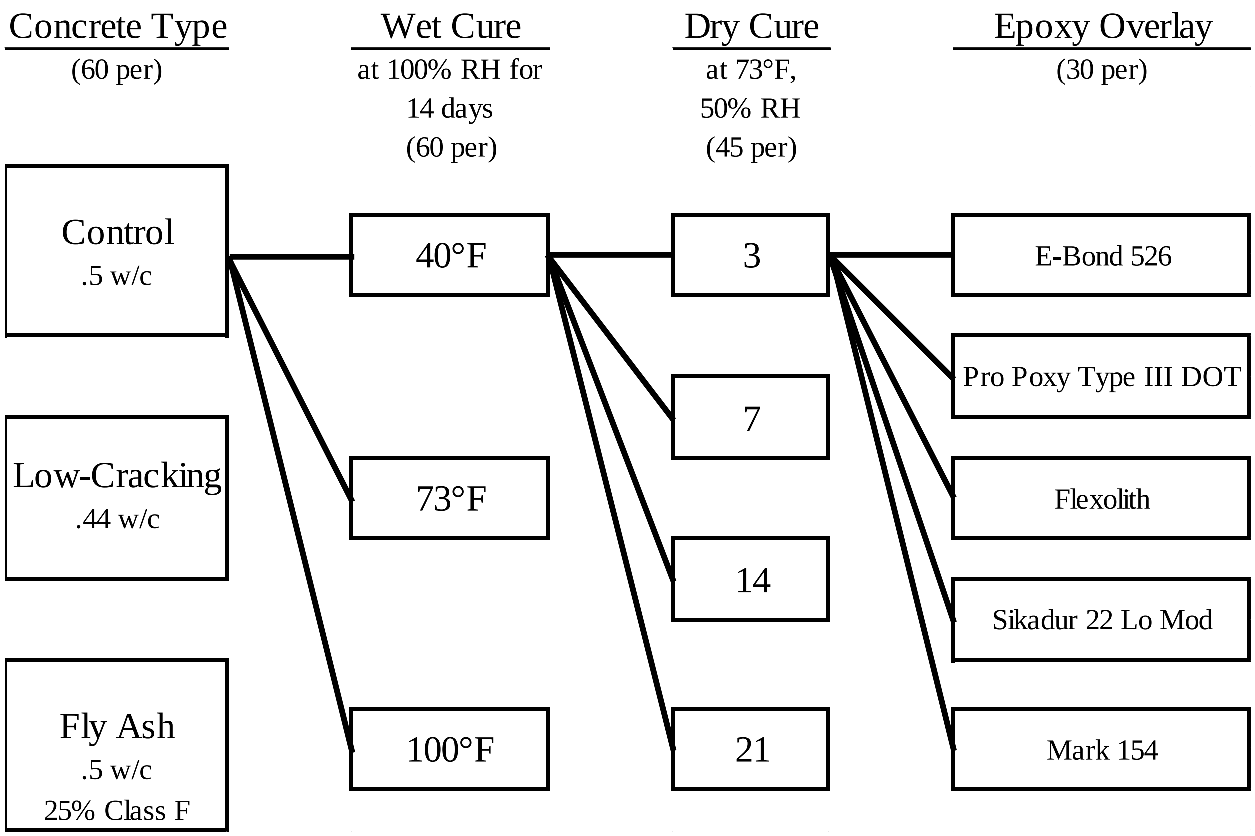

Figure 3.1: Testing Matrix

In order to produce each of the 180 possible testing conditions and test for both the moisture present and overlay bond strength, a slab thickness of 6 inches was selected. A 6-inch-deep slab would provide enough depth, but also reduce the weight of the slabs. The top surface of the slab had to provide enough area to accommodate both hot and room temperature pull-off tests. KDOT’s Kansas Test Method KT-70 (2014; Appendix I) states that four pull-off tests must be conducted for each test patch and the three highest values should be used to calculate tensile rupture strength. Therefore, eight pull-off tests were performed on each slab; four at a hot temperature and four at room temperature. Four of each pull-off tests at each temperature allowed for one pull-off in each temperature set to fail. Three successful pull-off tests are enough to still calculate an accurate average. KDOT’s Kansas Test Method KT-70 also states that a test patch size of 1.5×3 ft must be selected. A slab of that size and weight would create problems due to storage restrictions within both the wet and dry curing locations. Instead, a more modest size of 12×18 inches was selected as shown schematically in Figure 3.2. Figure 3.3 shows a picture of a specimen. This size fit much easier within the curing locations, and only weighed approximately 110 lbs instead of 330 lbs.

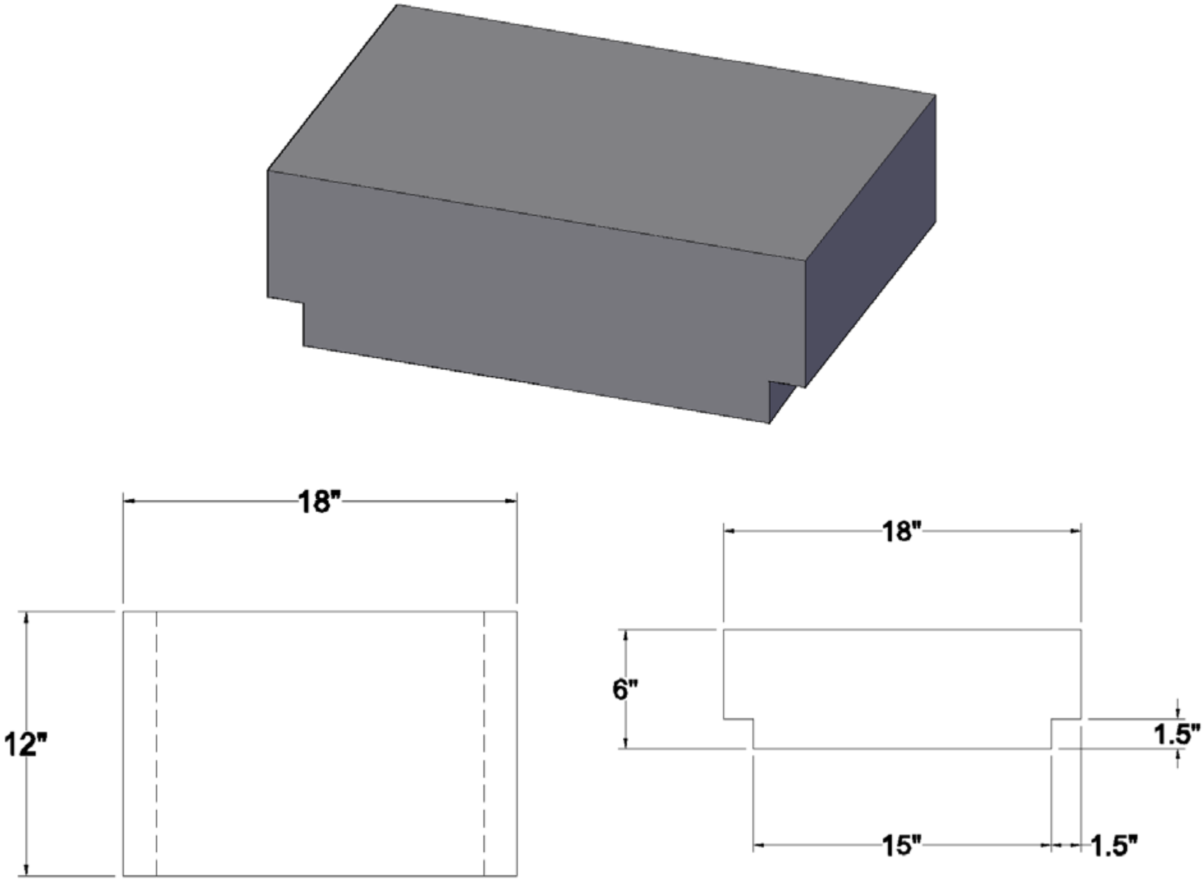

Figure 3.2: Slab Dimensions

Figure 3.3: Slab after Wet Curing

The labeling system that was implemented simplified each of the conditions the slab was to undergo, for example C-40-7-1. The first value refers to the concrete mixture: C for control, L for low-cracking, or F for fly ash. The second value is the wet cure temperature at which the slab was cured at: 40 for 40°F, 70 for 73°F, and 100 for 100°F. The third value is the duration of drying: 3, 7, 14, or 21 days. The fourth value refers to the epoxy overlay system to be placed on the slab: E-Bond 526, Pro-Poxy Type III DOT, Flexolith, Sikadur 22 Lo Mod, or Mark-154. Each overlay system was given a label of 1, 2, 3, 4, or 5.

To test concrete strengths for each curing method, concrete cylinders were made and tested to find compressive strength of the concrete. The concrete compressive strengths would need to be tested when the pull-off tests are to be conducted. Many tests result in concrete failures, and knowing the concrete strength would be beneficial. The determination was made that two concrete cylinders be tested for each slab upon completion of wet curing and two additional cylinders be tested when pull-off tests are conducted. When the slabs finish wet curing, compressive tests would provide a vantage point to discern wet cure temperature effects on the compressive strength of the concrete.

3.2 Concrete Mixes

A summary of concrete mixes used when batching the slabs is presented in Table 3.1. The mix for the low-cracking concrete mix was obtained from Midwest Concrete Materials (MCM) for a typical low-cracking bridge deck mix design. This mix contained 550 lbs of cement, a w/c of 0.44, 40% coarse aggregates, and 60% fine aggregates. Batches of this concrete mix were made to test this mix design. The test batches resulted in a very dry mix that had a lot of voids. The coarse aggregate was switched to 60% and the fine aggregate switched to 40%. The updated mix design eliminated those initial problems and provided concrete with a slump between 2 and 4 inches with great workability. The control was determined to have the same mix design, but with a 0.50 w/c. The fly ash would have a w/c of 0.50, but also have 25% of the cement (maximum allowed) swapped out for Class F fly ash. Water reducer amounts were determined based on the production of trial batches of concrete that achieved a slump between 2 and 4 inches.

Table 3.1: Concrete Mixes

	Control*	Low-Cracking*	Fly Ash*
Water/Cementitious Ratio	0.50	0.44	0.50
Cement	550	550	412.5
Fly Ash	0	0	137.5
Coarse Aggregate	1,837	1,858	1,884
Fine Aggregate	1,250	1,264	1,282
Air Content (assumed)	2%	2%	2%
Water Reducer (mL/kg-cementitious material)	600	800	0

*All units are lbs/yd^3 unless otherwise noted

3.3 Concrete Materials

In this study, only materials that met KDOT's *Standard Specifications for State Road & Bridge Construction* (KDOT, 2007) were used in the concrete mixes. Ash Grove portland cement Type I/II, a prequalified portland cement (KDOT, 2013b), was used as the cement in the concrete. A prequalified fly ash from Ash Grove called Durapoz F was used in the concrete mixture (KDOT, 2013a). The fine aggregate used in the concrete mixtures was a concrete sand from Midwest Concrete Materials and met both ASTM C33 FA and KDOT's FA-A size requirements. The requirements are located in the Section 1102 revision. CA-5 crushed limestone was used as the mixture’s coarse aggregate, meeting KDOT’s CA-5 specifications in the Section 1102 revision (KDOT, 2007). The water reducer selected was Daracem 65. It is manufactured by W. R. Grace & Company and is a mid-range water-reducing admixture that has been prequalified by KDOT (KDOT, 2014).

3.4 Epoxy-Polymer Overlay Systems

The epoxy-polymer overlay systems that were selected were all prequalified epoxy-resin-base bonding systems for KDOT: E-Bond 526, Pro-Poxy Type III DOT, Flexolith, Sikadur 22 Lo Mod, and Mark-154 (KDOT, 2011). The epoxy properties for each of the five overlay systems are shown in Table 3.2. KDOT has its own specifications that must be abided by when applying any type of multi-layer polymer concrete overlay.

Table 3.2: Epoxy Overlay Properties

			Epoxy 1		Epoxy 2		Epoxy 3		Epoxy 4		Epoxy 5	
Compressive Modulus			690,000 psi	14 days	80,000 psi		120,000 psi		125,000 psi	7 day		
									166,000 psi	28 day		
Compressive Strength			1,000 psi	3 hrs			5,000 psi		2,100 psi	16 hrs	8,500 psi	8 hrs
			5,000 psi	24 hrs					3,400 psi	1 day		
			6,500 psi	7 day					6,500 psi	3 days	10,500 psi	48 hrs
Tensile Strength			2,500-5,000 psi	7 days	3,000 psi		2,700 psi		5,900 psi	14 days	2,500 psi	
Bond Strength			1,600 psi	2 days	3,200 psi	14 days	2,100 psi	2 days	1,600 psi	14 days	500 psi	24 hrs
Absorption			0.40%	7 days	0.20%		<.5%	24 hrs	0.23%	24 hour	Max 1.0%	
Elongation			30-80%		50%		30-60%		30%		45-55%	
Gel Time			15-30 minutes		15 min	60 gm @73F	>30 min		30 minutes	200 gram mass	20 minutes	at 75° ±2°F
Coverage	Course 1	Epoxy	2.5 gal/100 sq ft		1 gal/40 sf		40-45 sq ft/gal		-		35 sf/gal	
		Aggregate	10 lbs/sq yd		10 lbs/sq yd		1.0-1.5 sq ft/gal		-		15 lbs/sq yd	
	Course 2	Epoxy	5 gal/100 sq ft		1 gal/20 sf		22-25 sq ft/gal		-		15 sf/gal	
		Aggregate	14 lbs/sq yd		14 lbs/sq yd		1.5-2.0 sq ft/gal		-		15 lbs/sq yd	

All information in this table comes from data sheets for each of the five epoxy overlay systems: E-Bond Epoxies, Inc; Dayton Superior Corporation; The Euclid Chemical Company; Sika Corporation; and Poly-Carb, Inc.

Chapter 4: Testing Process

The process for testing both the moisture contents and overlay bond process was conceived to address all project needs while utilizing available equipment. The amount of slabs that could be cast at a time was limited to the available space in the curing locations. After examining all aspects of the process and resolving test slab complications, the process was completed as described in the following sections.

4.1 Casting Slabs

Casting concrete slabs for the epoxy polymer overlay to be placed was the first step. Reusable, transportable forms were built to accommodate 12×18×6-inch-deep slabs as shown in Figure 4.1. Limited space in the wet and dry curing locations allowed for only a limited number of slabs to be cast per batch. Many casting days and various sets of forms were required to accommodate the 180 slabs to be cast. The forms had dimensional restraints too since they had to be placed within the wet cure locations.

Figure 4.1: Forms Built to Accommodate the 12×18×6-Inch Slabs

An additional piece of wood was placed along the ends of the 12-inch length inside each form allowing for handles in the slabs once the forms were stripped away. The handles provided a place to lift and transport the slabs without affecting slab depth function. Space for the handles is shown in Figure 4.1. All corners of the forms were sealed with a waterproof silicone caulk to seal cracks.

A length of twine, acting as a guide wire for a thermocouple, spanned the form at 1 inch below the top of the forms as shown in Figure 4.2. The thermocouple is required to measure internal temperature of the concrete slabs later in the testing process. The thermocouples were set 1 inch below the concrete surface. To achieve this depth, holes were drilled on the form sides at a depth of 1 inch and twine was strung from side to side. The twine was drawn taut and taped to the sides of the forms. Thermocouple wire was then placed through the hole on one side of the form until the end of the wire reached the center of the form. The thermocouple wire was taped to the twine. Both holes in the forms were sealed with caulk.

Figure 4.2: Thermocouple Wire Setup Within Slab Forms

Materials to create the concrete were placed inside the day before mixing, thereby equalizing the temperature of all the materials. After weighing out proportions, the concrete was mixed with a 12 ft^3 Mud Hog mixer shown in Figure 4.3. The mixing was performed as follows:

1. Admixture was poured into batch water.
2. One-third of coarse and fine aggregates were placed into the mixer.
3. One-half of total batch water was added, ensuring all admixtures were added.
4. Aggregates and water were mixed for 1 minute to thoroughly wet the aggregates.
5. A maximum of 50 lbs of cement and an adequate amount of batch water were added to keep the mix wet. Mix for 30 seconds. (If using fly ash, add the fly ash in this step prior to the cement.)
6. Step 5 was repeated until all cement was in the mixer.
7. Coarse and fine aggregate were alternately added to the mix until all aggregate was in the mixer (3-5 minutes). The remaining batch water was added as needed.
8. Mixing continued for 2 minutes.

Figure 4.3: Mud Hog Mixer Used to Batch Concrete

Upon completion of mixing, a slump test was conducted with a target slump between 2 and 4 inches. The slabs were then cast and the slab surface was smoothed. A small aluminum plate with a slab label was placed in the bottom right corner of the slab as seen in Figure 4.4. Dampened burlap was laid over the concrete to begin wet curing and a sheet of plastic was taped over the burlap to seal in the moisture. The forms and newly-cast concrete slabs were immediately transported to the wet cure location so all curing would occur at the designated temperature.

At this same time, 4×8-inch concrete cylinders were cast. The cylinders were covered with a lid and sealed with tape. Labels were placed on the cylinders to keep track of which slab they corresponded to. After this point, the cylinders did not leave the slabs they were cast with. They went to the same wet cure location and then to the drying location.

Figure 4.4: Slab Label Cast into the Concrete

4.2 Curing the Slabs

As soon as the slabs had been sealed in plastic, they were moved to one of three prescribed wet cure locations: a refrigerated room, a moist cure room, and an oven. The three locations are shown in Figure 4.5 and Figure 4.6. The slabs cured in their locations for one day before the forms were removed. Slabs located in the 73°F wet cure room were allowed to remain, while the 40°F and 100°F slabs were placed in plastic totes, as shown in Figure 4.7. Wet burlap was placed within the bin with the slab and the tote was sealed with duct tape. The slabs inside the totes were checked on regularly to ensure that the burlap remained wet. The slabs were wet cured for 14 days after casting before they were to begin drying.

Figure 4.5: Wet Cure Locations for 40°F Refrigerator (left) and 73°F Moist Room (right)

Figure 4.6: Wet Cure Location for 100°F Oven

Figure 4.7: Slab Placed Inside a Bin for Wet Curing

Upon completion of wet curing, the slabs were taken out of their bins and allowed to dry enough so that no moisture was present on the sides of the slabs. For a bridge deck, the bottom and sides of an area 12×18 inches would be encapsulated in concrete. To simulate this condition, the slabs were completely wrapped in plastic, with the exception of the top surface, to prevent moisture from escaping and causing excess drying not typical in a larger slab. Gorilla tape was used to secure the plastic to the slab. Figure 4.8 and Figure 4.9 show a slab before and after wrapping in plastic. All slabs, no matter the wet cure temperature, were placed in a room at 73°F and 50% relative humidity as shown in Figure 4.10 for the prescribed 3, 7, 14, or 21 days.

At this time, all of the cylinders were broken out of their forms. The cylinders had to remain in their forms for the whole wet cure time in order to seal the cylinders and allow for wet curing. Two concrete cylinders were tested for each group of slabs being removed from their respective wet cure locations. In some cases, three or more slabs were all wet curing for the same time period and also in the same wet cure location, so instead of testing two cylinders for each slab, two cylinders were tested for all of them. Cylinders were tested at a maximum rate of 450 lbs/sec. The resulting strengths were labeled as wet cure strengths.

Figure 4.8: Slab After Wet Curing

Figure 4.9: Slab Wrapped in Plastic to Dry

Figure 4.10: Drying Location

4.3 Moisture Reading and Surface Preparation

Once the slabs reached their prescribed drying time, they were removed and prepared for overlay installation. A steel wire brush was used to roughen and clean the slab surface of debris, such as single fibers of burlap that adhered to the slab during curing. The surface was then sandblasted to a surface roughness of 3 to 5 on the ICRI roughness scale with the sandblaster shown in Figure 4.11. A before-and-after photo of the sandblasting is shown in Figure 4.12. The achieved roughness of 3 to 5 provided a worst-case scenario for surface roughness, and thereby making the findings from this study conservative. The surface of a roughened slab is shown in Figure 4.13 and a close-up is shown in Figure 4.14. KDOT specifications call for an ICRI roughness of 6 to 7 (KDOT, 2007, Section 729).

Figure 4.11: Sandblaster

Figure 4.12: Before (left) and After (right) Sandblasting a Slab

Figure 4.13: Sandblasted Surface with Visible Large Aggregates

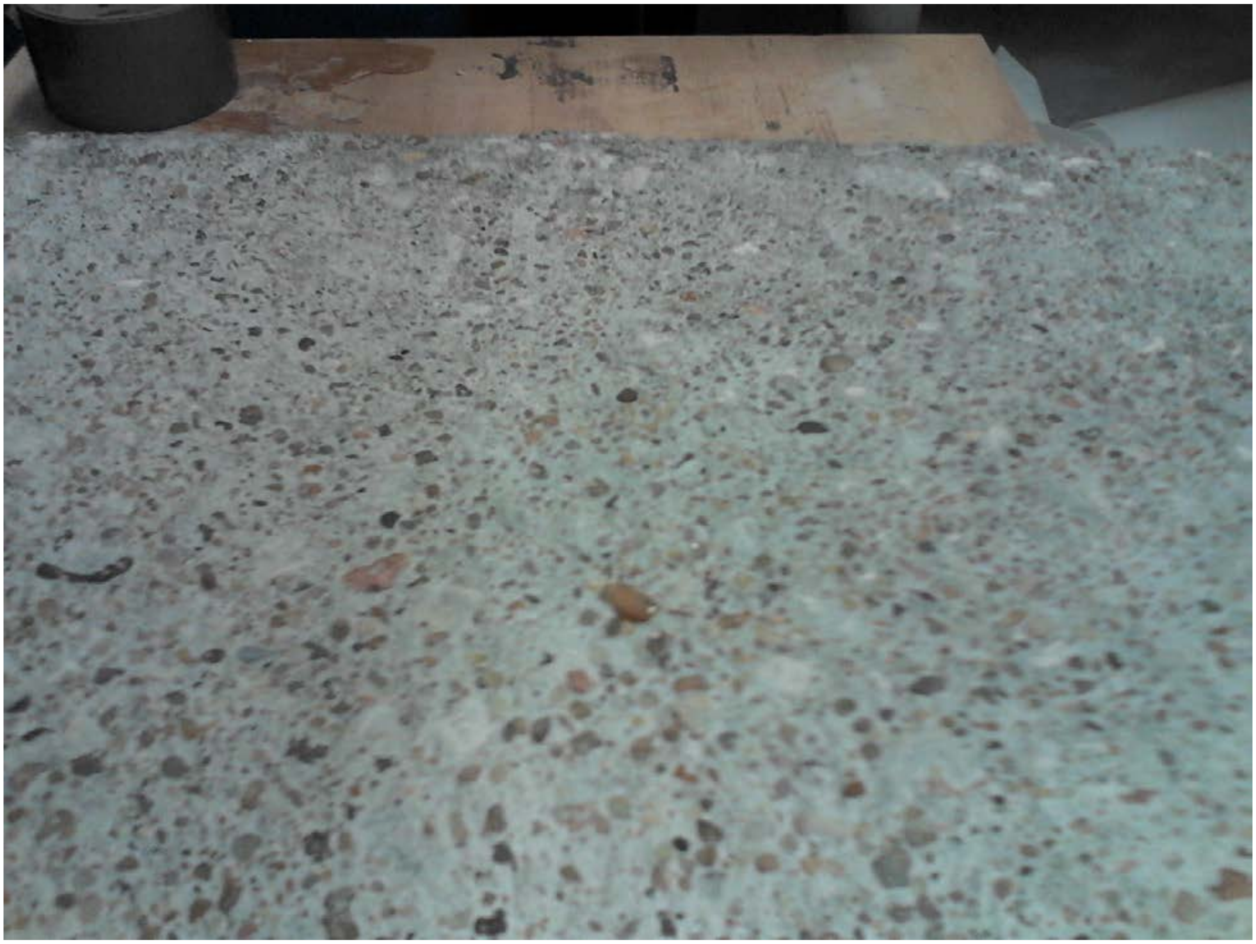

Figure 4.14: Close Up of Concrete Surface After Sandblasting

Moisture in the top surface of the concrete was read by a Tramex CMEXpert II concrete moisture meter shown in Figure 4.15. The moisture meter reads the moisture content by reading the electrical impedance measured across multiple electrodes on the meter. The electrodes create a low frequency alternating electrical field. The CMEXpert II readings can vary, so only the highest readings should be recorded. Six zones were created on top of the slab and a moisture reading was taken in each zone a minimum of three times. The highest reading within each zone was recorded, and the overall slab moisture average was found from these six readings. Moisture readings were taken after sandblasting on all slabs. After looking at the results of the after-sandblasting moisture readings, it was determined that the compressed air and sand being blown onto the concrete slab surfaces might be drying them out. Moisture readings were taken both prior to sandblasting and after sandblasting on the fly ash slabs to see how much sandblasting was drying out the slab surfaces.

Figure 4.15: Tramex CMEXpert II Instrument Used to Take Moisture Readings

4.4 Overlay Placement

After roughening and moisture reading, the slabs were ready for their overlay. Amounts of both epoxy components were portioned out at a ratio of 1:1 by volume by using a tablespoon measuring spoon.

Because of the intention to make all overlay systems uniform, the epoxy proportions would be 2.5 fl oz per component for the first course and 5.0 fl oz per component for the second course. These proportions were equivalent to a coverage rate of 40 ft^2/gal for the first course and 20 ft^2/gal for the second course. These coverage rates for each course either fell within the recommended range or close to the recommended amounts previously mentioned in Chapter 3. Parts A and B were then mixed together vigorously for 3 minutes by hand, because the mixed amounts were too small to mix mechanically as recommended. If the small quantities of epoxy had been mechanically mixed, air would become entrained, causing a loss of bonding surface and other complications.

Epoxy was poured evenly over the slab surface and allowed to spread out for a few minutes. The epoxy was then manually dispersed evenly over the entire surface. Ten minutes after initial mixing, aggregate was spread over the surface by hand. The aggregate rate used for all systems was 0.55 lbs per slab for the first coating and 0.88 lbs per slab for the second coating. The aggregate application rates are equivalent to 10 lbs/sq yd and 16 lbs/sq yd for the first and second courses respectively. Similar to the epoxy amounts, these were set within the recommended range or close to the recommended amount. Figure 4.16 and Figure 4.17 show the first and second courses of the epoxy and aggregate layers.

All overlay systems were placed in 70-75°F temperature with a curing time of 2.5 hours between the first and second courses. The second course cured overnight.

Figure 4.16: Placement of Course One of Epoxy (left) and Aggregate (right)

Figure 4.17: Placement of Course Two of Epoxy (left) and Aggregate (right)

4.5 Testing Procedure

After curing overnight for at least 15 hours, the overlay was ready to be cored. The testing procedure conducted was similar to KDOT's KT-70 (2014) and ACI 503R, Appendix A of the ACI Manual of Concrete Practice (ACI Committee 503, 1993). Applied changes include sealing the cores with silicone caulk and heating the slabs to 122-125°F. Both changes increased potential water vapor pressure at the interface between the concrete and overlay. Caulk sealed in the moisture to replicate the overlay prior to being cored.

A diamond-tipped concrete core drill bit with an interior diameter of 2 inches was used to drill through the polymer overlay to a depth of 0.5 inches into the concrete as shown in Figure 4.18. Water was not used when coring to avoid adding moisture not already present within the concrete. Dust from the cores was blown out using compressed air.

Figure 4.18: Coring Setup (left) and a Core Through the Overlay into the Concrete (right)

The cores were filled with silicone caulk directly after coring as shown in Figure 4.19. The caulk was allowed to harden and dry for a couple hours to avoid interference with mounting the pull-off caps. Aggregate on the surface of the overlay created a surface with sharp rocks sticking out. Pull-off cap placement directly on a core would misalign the cap with the axis of the core; therefore, any aggregates that aided in misaligning the cap from the axis of the core were chipped off with a hammer and chisel. Once enough aggregates were chipped away to provide a surface on which the cap can sit level, the caps were ready to be mounted. Occasionally a small part of the overlay at the edge of the core would chip off, but otherwise there were no ill effects from chipping the aggregates. Once the caps sat level on the cores, they were ready to be mounted. The pull-off caps were 2-inch diameter aluminum pucks with a flat bottom and a hole on top in which to screw the pull-off equipment. Prior to placing, the caps were soaked in acetone and scraped to remove existing epoxy from prior use of the caps. The caps were sandblasted to create a clean, roughened surface for the adhesive to bond to. After cleaning, the caps could effectively provide a stronger bond to the adhesive than either the overlay's bond to the concrete or the strength of the concrete tensile strength. The same epoxy used for the overlay was used for the adhesive to mount the pull-off caps. No failures due to the pull-off cap delaminating from the overlay were recorded when the procedure was correctly followed. The epoxy was measured and mixed in the same manner as described in Section 4.4 Overlay Placement. After mixing was complete, the epoxy was spread over the core and pull-off cap to ensure complete coverage as shown in Figure 4.20 and Figure 4.21. Caps were placed on the core and kept level while curing. Any epoxy that spilled onto the silicone caulk or onto the rest of the overlay was not considered to cause misleading results. When performing the pull-off, the caulking added minimal strength to the final pull-off result; when the epoxy had to "bridge" over the caulk, that epoxy was placed under shear stress. The shear strength of the epoxy did not substantially add to the pull-off strength. The epoxy used as adhesive was allowed to cure for a minimum of two hours prior to placing the slabs under heat lamps.

Figure 4.19: Placement of Silicone Caulk to Seal the Cores

Figure 4.20: Application of Adhesive Epoxy to Mount the Aluminum Caps

Figure 4.21: Slabs Before and After Placing Pull-Off Caps

4.6 Temperature Preparation

The slabs were placed under heat lamps to replicate the sun’s heat during summer on the bridge deck. The heat lamps were rectangular with 120V, 350W lamps to provide even distribution of heat to the whole surface of the slab. The lamps were placed 10.5 inches (from the bottom of the rectangular lampshade) above the slab surface, producing an internal temperature of 122-125°F one inch below the concrete surface after 12-18 hours. Thermocouple wires cast into the concrete were connected to a computer to read temperatures. In order to protect the aluminum caps from heating up more quickly than the overlay, heat shields comprised of halved plastic cups protected the caps from direct exposure to the heat. Heat allowed directly to the aluminum caps produced thermal stresses because of differential heating, which produced a low-strength bond between the aluminum cap and epoxy adhesive. The heating setup is shown in Figure 4.22 and the thermocouple connected to the computer is shown in Figure 4.23.

Figure 4.22: Slabs Placed Under Heat Lamps with Shield Protectors Over the Caps

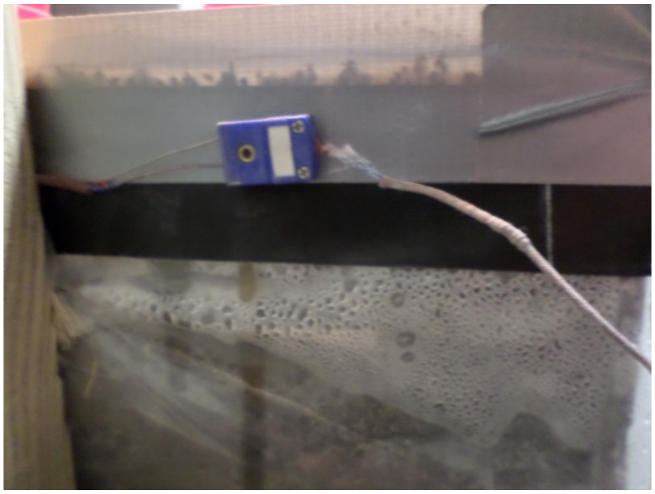

Figure 4.23: Thermocouple as the Slabs are Heated

4.7 Pull-Off Tests

Pull-off tests were performed using a DYNA Pull-Off Tester with Digital Manometer which utilized a hydraulic crank to pull attached pull-off caps in tension. Tensile force was measured digitally in pounds per square inch. The pull-off tester is shown in Figure 4.24.

Figure 4.24: Pull-Off Tester

Pull-off testing was performed on four cores per slab immediately after a slab reached 122-125°F and was removed from under the heat lamps. The remaining four cores were tested the following day, approximately 24 hours after initial tests were completed. This testing procedure provided four measurements for pull-off strength when the slabs are in a “worst-case scenario” and four measurements when the slab has undergone a “worst-case scenario” and returned to temperatures likely to produce strengths higher than the first four measurements.

A connecting screw was used to connect the pull-off cap to the pull-off tester. The screw was screwed into the cap while the other end attached to the pull-off tester by a ball-bearing system, allowing the tester to account for small eccentricities that are too small to correct. Figure 4.25 shows the screw attached to a cap ready for the tester.

Figure 4.25: Pull-Off Cap Ready to be Tested

The pull-off tester did not have an automated system with which to control the testing by force or displacement. KDOT's Kansas Test Method KT-70 (2014) states a tensile load should be applied at 100 ± 10 lbs every five seconds. In order to decrease variability, a testing procedure based on rotation of the crank was utilized: one full crank rotation for every one second. A metronome set at 60 beats per minute was used to match one rotation with one second. The test became displacement controlled by controlling the rotation of the crank.

After completion of a test, the pull-off strength in psi and failure type were recorded, and the coverage area for each failure was recorded for each pull-off. In many instances, there was failure both in the concrete and at the bond interface as shown in Figure 4.26. According to KDOT's KT-70 (2014), five failure types are possible for each pull-off. Each failure type is shown in Figures 4.26 through 4.28. The five types of failure are:

- Type 1: Failure in the concrete at a depth greater than or equal to 0.25 inches over more than 50% of the test area.
- Type 2: Failure in the concrete at a depth less than 0.25 inches over more than 50% of the test area.
- Type 3: Separation of the polymer overlay from the concrete surface.
- Type 4: Failure within the polymer overlay.
- Type 5: Failure of the test adhesive.

Figure 4.26: Failure Type 1 (left) and Failure Type 2 (right)

Figure 4.27: Failure Type 3 (left) and Failure Type 4 (right)

Figure 4.28: Failure Type 5 (left) and a Failure with Both Type 2 and Type 3 (right)

Average pull-off strengths for each slab were found based on the average of Type 1, 2, and 3 failures. Type 4 failures were not used in calculation because it means the overlay was either not mixed, placed, or cured correctly. Similarly, Type 5 failures meant the adhesive was either not mixed, placed, or cured properly and the results were not used in calculation. When the pull-off cap failed during testing, the failures were denoted as Type 6. Type 6 failures were very rare and only occurred twice. A properly prepared concrete surface and applied polymer overlay should result in a Type 1 failure. Type 1 failures less than 250 psi result from weak concrete rather than a poor overlay bond; therefore, they should not be used in calculations (KT-70, 2014). Each slab for hot and room temperature pull-offs required a minimum of three pull-off tests to be an acceptable failure type. If less than 3 pull-off tests were acceptable, the entire slab was deemed unacceptable and was recast and retested.

Concrete cylinders were tested the same day the pull-off tests were conducted. Two cylinders were tested for each slab using the same procedure as the tests that were conducted after wet curing.

Chapter 5: Results

5.1 Moisture Readings

As described in Section 4.3 Moisture Reading and Surface Preparation, a TRAMEX CMEXpert concrete moisture meter was used to measure moisture present in the top layer of a concrete slab. Readings were taken after sandblasting the slabs, but prior to placing the polymer overlay. Multiple readings were taken within the six zones on the slab surface, the maximum value from each zone was recorded, and the average was found for each slab. Figure 5.1 plots the average moisture percentage in the concrete with how many days the slabs were dried. Moisture percentages shown are the average of all slabs, with the only difference coming from the number of drying days. Results indicate slight decreases in moisture readings as drying time increases. As shown in Table 5.1, the moisture percentage in the concrete decreases by 0.04 to 0.46% per day of dry curing. Drying occurred three to ten times faster during the first 14 days than during the last 7 days. Drying was expected to occur faster initially since more moisture was available to be lost. To see the effect the concrete type and wet cure temperature had on the moisture content in the slabs, each condition was examined more in-depth.

Table 5.1: Overall Moisture Percentages

Overall Moisture Percentages				
Drying Time (Days)	**Overall Moisture %**	**Percentage Decrease from Previous**	**Percentage Decrease from Previous (Per Day)**	**Percentage Decrease from 3 Day**
3	3.576			
7	3.556	-0.55%	-0.14%	-0.55%
14	3.441	-3.22%	-0.46%	-3.76%
21	3.433	-0.25%	-0.04%	-3.99%

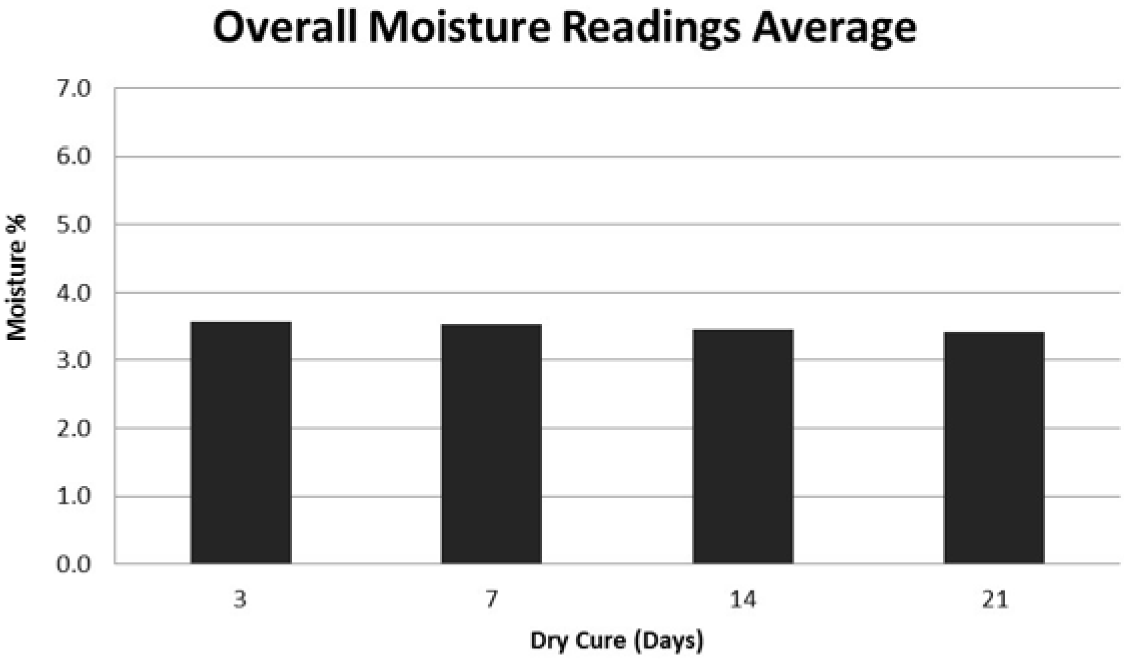

Figure 5.1: Overall Average of Moisture Readings

Concrete type could potentially affect moisture content in the concrete while drying due to the concrete's makeup. The control and fly ash concretes were batched with a 0.50 w/c, while the low-cracking contained a 0.44 w/c. As shown in Figure 5.2, the low-cracking mixture consistently provided higher moisture contents than the other two types of concrete. The fly ash consistently produced the lowest moisture contents. The largest difference in moisture content between the three types of concrete occurs at the 7-day drying time. The low-cracking slabs contain an average of 3.79% moisture, while the control and fly ash concretes contain an average of 3.49% and 3.39% moisture, respectively. The pore structure within 0.50 w/c ratio concretes has more voids and could allow for quick evaporation.

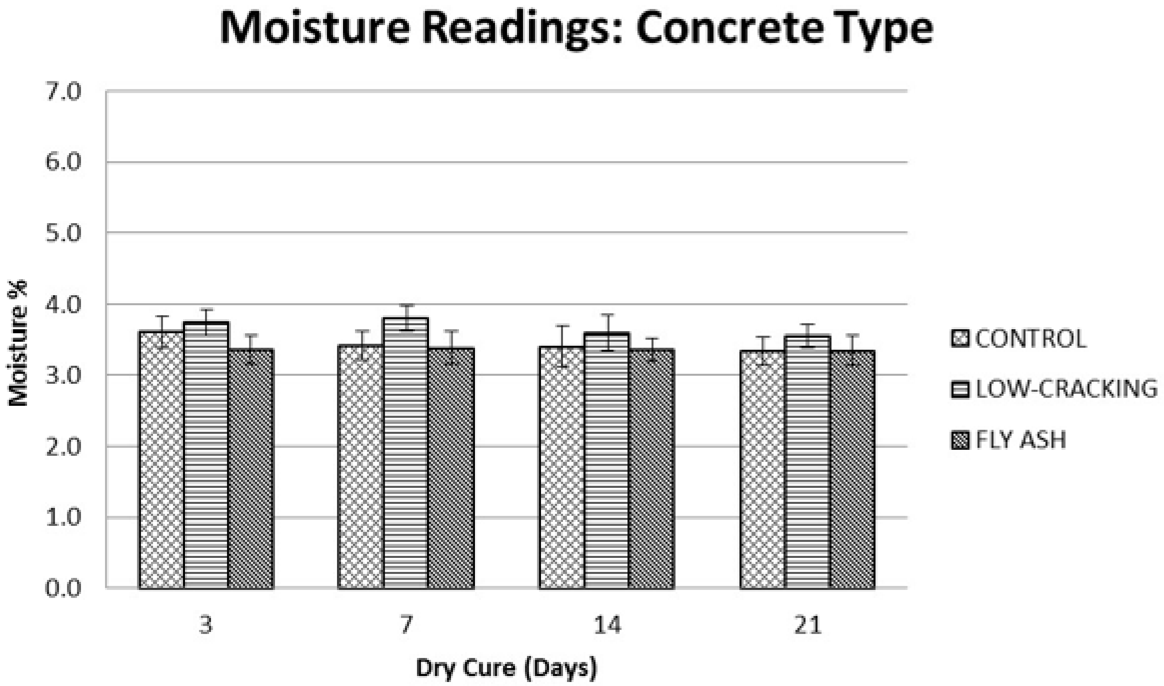

Figure 5.2: Average Moisture Readings Separated by Concrete Type

Moisture contents remain similar after categorizing them into various concrete types. Results showed that sandblasting the concrete surface lowered the moisture content of the slab and showed all readings to be similar. On the fly ash concrete slabs, moisture readings were taken prior to sandblasting and after sandblasting. The same process of collecting moisture readings from the slabs after sandblasting was used prior to sandblasting. Figure 5.3 shows the difference between taking moisture readings before and after sandblasting the slabs. Moisture readings were much higher prior to sandblasting. After 3 days of drying, moisture prior to sandblasting averaged 4.21%, while after sandblasting, moisture in the same slab averaged 3.37%. Standard deviation bars also show consistent averages: Averages after sandblasting had standard deviations between 0.167 and 0.222, and standard deviations from averages before sandblasting were 1.363 (3-day), 0.917 (7-day), 0.307 (14-day), and 0.295 (21-day). Large standard deviations from the 3- and 7-day drying indicate that a portion of the slabs dried more quickly, while others demonstrated wet spots. After 14 days of drying, the standard deviation decreased. The conclusion can be made that between seven and 14 days of drying, the slabs dried enough to have consistent moisture contents with each other.

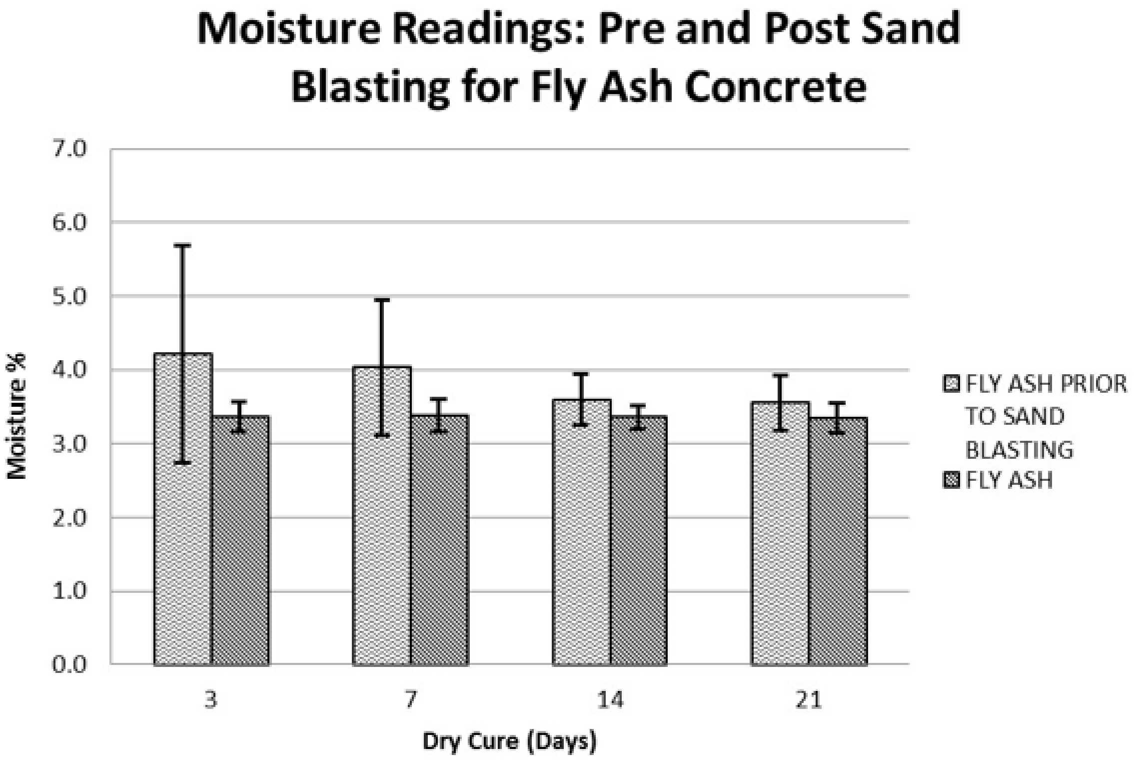

Figure 5.3: Moisture Readings: Pre- and Post-Sandblasting for Fly Ash Concrete

The temperature at which wet curing occurs could also affect moisture content of the slabs. In the same format as Figure 5.4, average moisture readings are categorized by wet cure temperature. The moisture readings are consistent from 3 days to 21 days, similar to Figure 5.4. The largest variance was observed for the 73°F wet cure slabs which ranged from 3.76% moisture to 3.38% moisture at 3 and 21 days, respectively. Neither the 40°F nor the 100°F varied more than 0.1% from 3 to 21 days of drying. As previously stated, sandblasting the surface could have produced more uniform results.

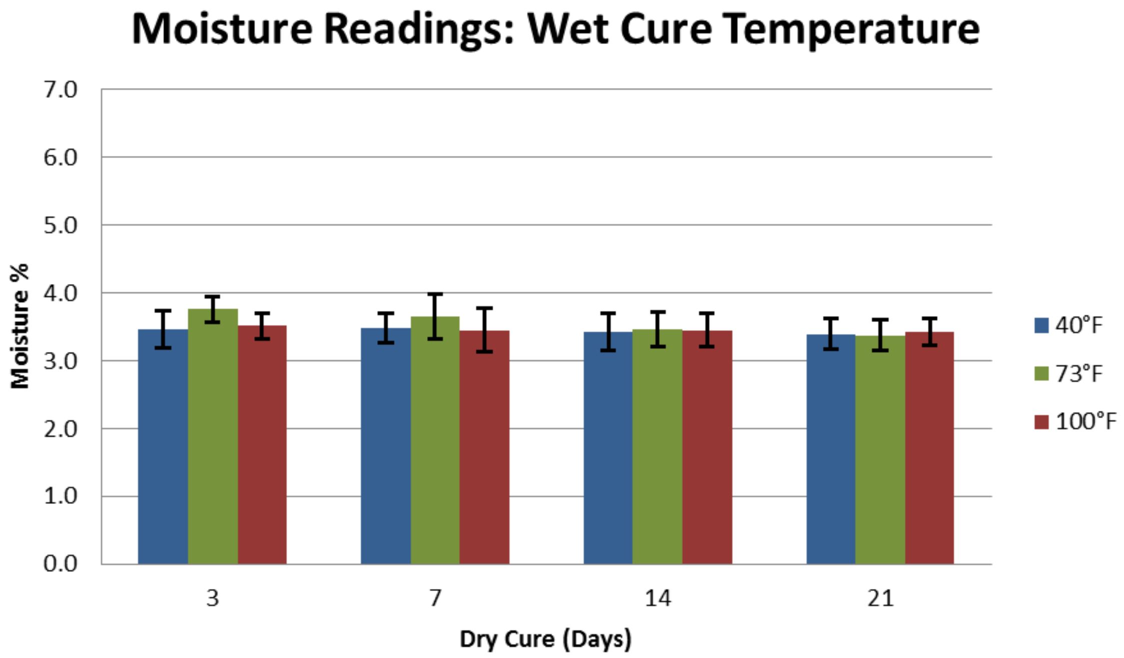

Figure 5.4: Moisture Readings: Wet Cure Temperature

Results shown in Figure 5.5 for the fly ash concrete moisture readings prior to sandblasting can be split between the three wet cure temperatures. The Figure shows averages from the 40°F and 100°F wet cure temperatures varying slightly from Day 3 to Day 21 with a limited range of 3.72% to 3.44% for the 40°F and 3.49% to 3.38% for the 100°F. Conversely, the 73°F wet curing produced much higher moisture readings for 3 and 7 days of dry curing, with an average moisture reading of 5.82% and 4.97%, respectively. Moisture readings for the 73°F slabs remained only slightly higher than the 40°F and 100°F slabs at 14 and 21 days of drying.

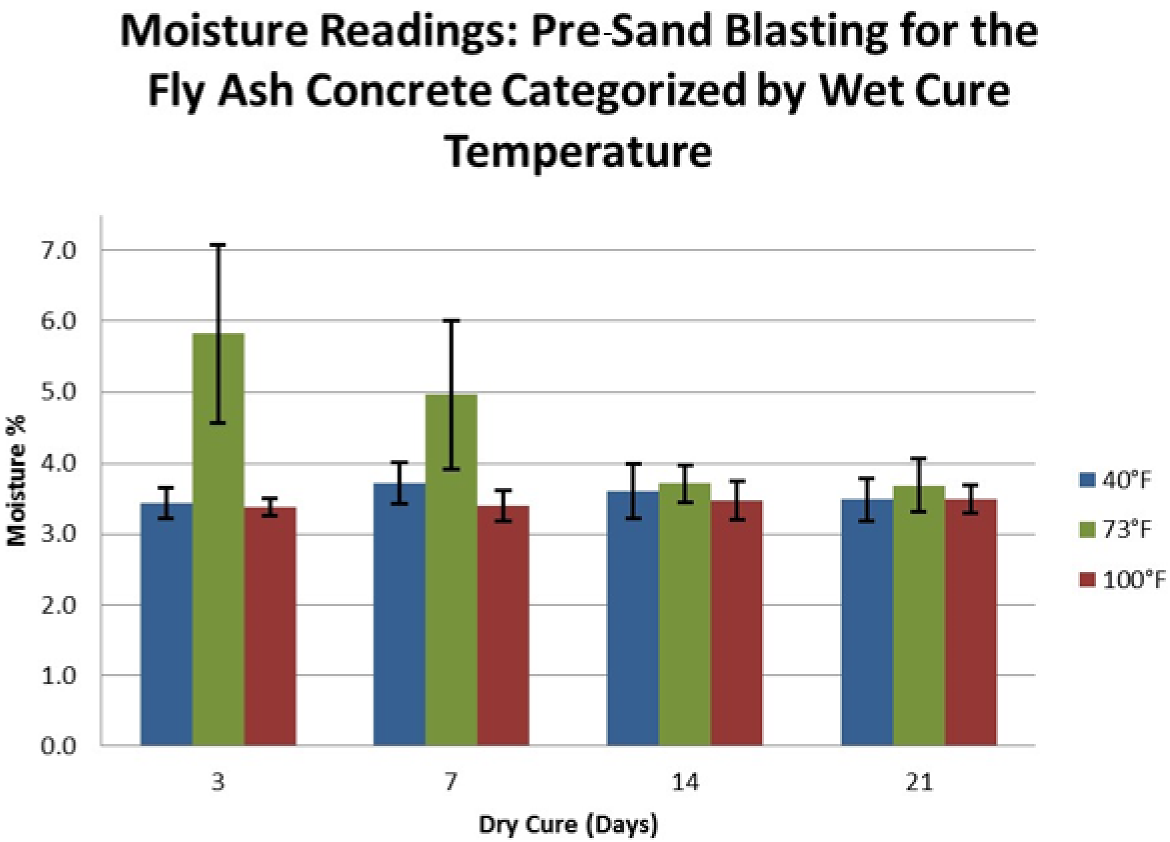

Figure 5.5: Moisture Readings: Pre-Sandblasting for the Fly Ash Concrete Categorized by Wet Cure Temperature

The difference in moisture readings could be due to several causes, including the wet cure environment. The 73°F slabs were wet cured in a moist room with a constant spray of mist. The 40°F and 100°F slabs were cured and sealed within a small bin with moist burlap because no moist room was available at 40°F or 100°F. A second cause for differences in moisture readings is temperature difference. The 40°F and 100°F slabs were forced to undergo a temperature change when placed in the 73°F drying location. The temperature change could have increased evaporation or bleeding from the slabs. The 73°F slabs did not undergo a temperature change and were allowed to dry under ideal circumstances.

Additional tests were conducted to more thoroughly understand how moisture affects the curing process of concrete. A few slabs dried for 21 days were tested periodically for moisture content throughout the dry curing time, thus offering insight as to how individual slabs dry.

Another test was performed to discern the correlation between moisture meter readings and actual moisture content within concrete. This test was conducted by casting concrete specimens that were smaller than the slabs. After wet curing, these specimens were allowed to dry at 73°F and 50% relative humidity or into an oven to dry out completely. Using the moisture meter, the specimens were continuously tested for moisture readings and weight to determine actual moisture content in the concrete. The full process and results are presented in Chapter 6.

5.2 Pull-Off Tests

Pull-off tests using the previously described procedure were conducted for all 180 slabs. Eight pull-off tests were conducted per slab, with four tested at the hot temperature (122-125°F) and four tested at room temperature (73°F ± 5°F). Results indicated that average strengths occurred in the concrete or at the bond interface. All failures in the overlay or test adhesive used to mount the aluminum pucks were viewed as inadequate. Strength in the concrete or bond interface could be stronger, but an early failure in the epoxy would show a lower pull-off test result than what the overlay bond is capable of. To demonstrate the range of pull-off tests and the average, standard deviation bars were added to all bar graphs.

An overview of all pull-off test results was compiled and is presented in Figure 5.6. The graph plots pull-off strength against the number of days the slabs were dried. In addition, hot and room temperature pull-off tests were split, and are shown in separate bars due to their large difference in their average pull-off tests. Each bar in Figure 5.6 consists of 180 individual pull-off tests from 45 slabs. As indicated in the Figure, pull-off tests at room temperature performed nearly twice as strong as the tests conducted at the hot temperature. Pull-off tests conducted at the hot temperatures averaged less than 250 psi, but room temperature pull-off tests averaged over 350 psi. In addition, pull-off tests gained strength with increased cure time. Table 5.2 shows the values depicted in Figure 5.6 and the percentage increase for each drying time. Using the 3-day drying time results as a base, hot temperature pull-off strengths increased by 13.8% after four additional days of drying and up to 40% after 11 additional days of drying. Room temperature pull-off tests showed a slight decrease in pull-off strength after four additional days, but gained over 9% after the entire 21 days of drying. For hot and room temperature tests, the largest increase in pull-off strength was noted from 7 days of drying to 14 days. Hot temperature pull-off tests gained 23.1%, while room temperature tests gained 6.6%. These results indicate that the hot temperature pull-offs have more potential to increase the pull-off strength when given more time to dry.

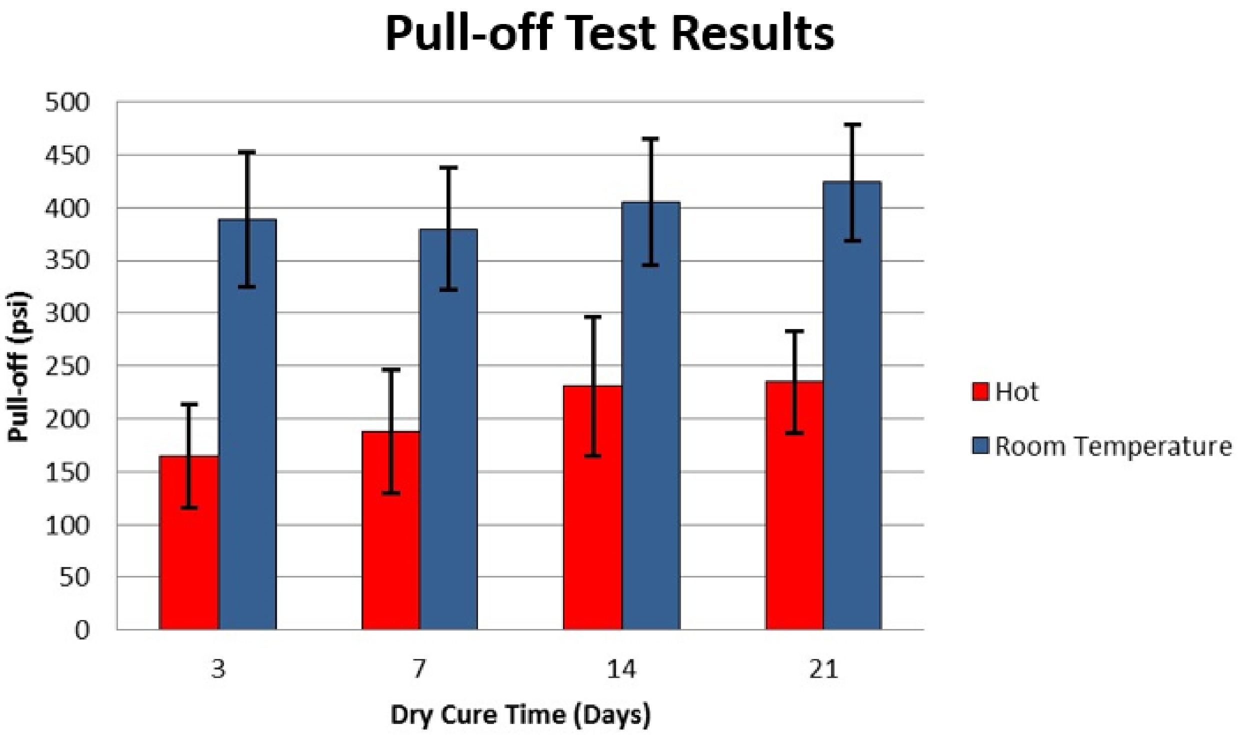

Figure 5.6: Pull-Off Test Results Overview

Table 5.2: Pull-Off Test Results Overview

	Hot Temperature			Room Temperature		
Drying Time (Days)	Pull-Off (psi)	Percentage increase from previous	Percentage increase from 3 days	Pull-Off (psi)	Percentage increase from previous	Percentage increase from 3 days
3	165			389		
7	187	13.8%	13.8%	380	-2.2%	-2.2%
14	231	23.1%	40.0%	405	6.6%	4.2%
21	235	1.8%	42.5%	424	4.7%	9.1%

Figure 5.7 and Figure 5.8 show pull-off test results as above, but the results are shown based on the concrete type. The three concrete mixes were control (0.50 w/c), low-cracking (0.44 w/c), and fly ash (0.50 w/c and 25% fly ash). Figure 5.7 shows pull-off results with respect to drying time. Drying times are further dissected between the three concrete types. Hot and room temperature pull-off results are grouped and shown separately in Figure 5.7 and Figure 5.8.

In Figure 5.7, pull-off strengths generally increase with time. The low-cracking and fly ash concretes continually increase with time, while the control concrete peaked at 14 days. The fly ash concrete consistently produced the highest or second highest average pull-off strengths. The low-cracking concrete surprisingly demonstrated the worst performance, even though it had the lowest water-to-cement ratio. Figure 5.8 shows results for room temperature pull-off tests for each concrete type. Again, room temperature tests result in higher pull-off strengths. The fly ash concrete also produced the highest pull-off test results out of the three concrete types. Each bar in Figure 5.7 and 5.8 represents 15 slabs or 60 pull-off tests.

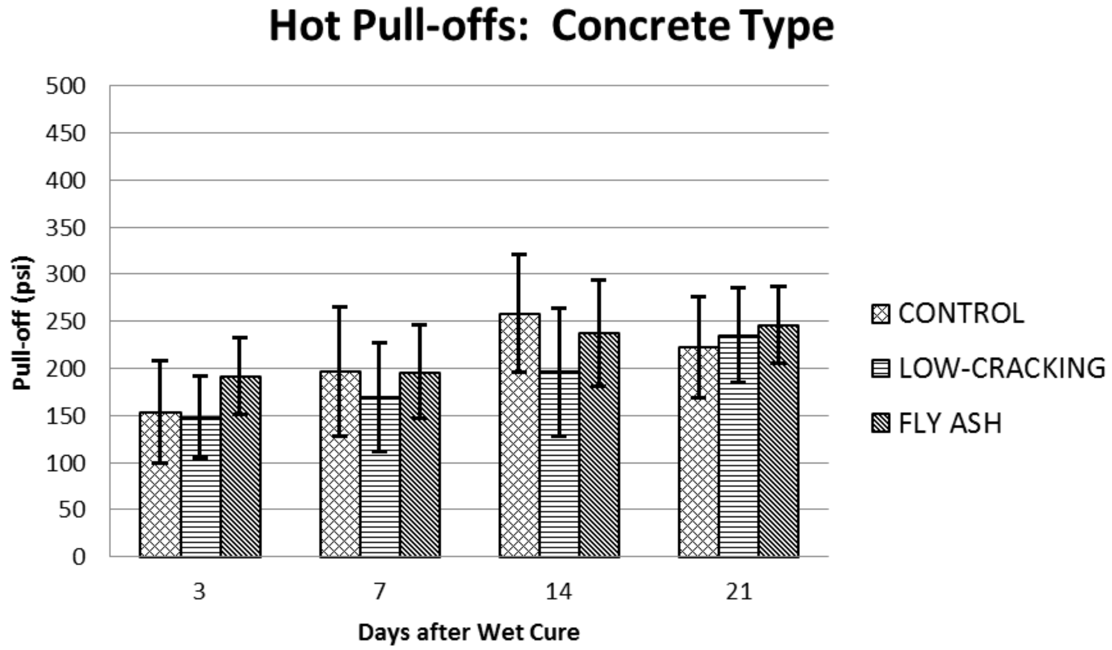

Figure 5.7: Average of Hot Pull-Offs Based on Concrete Type

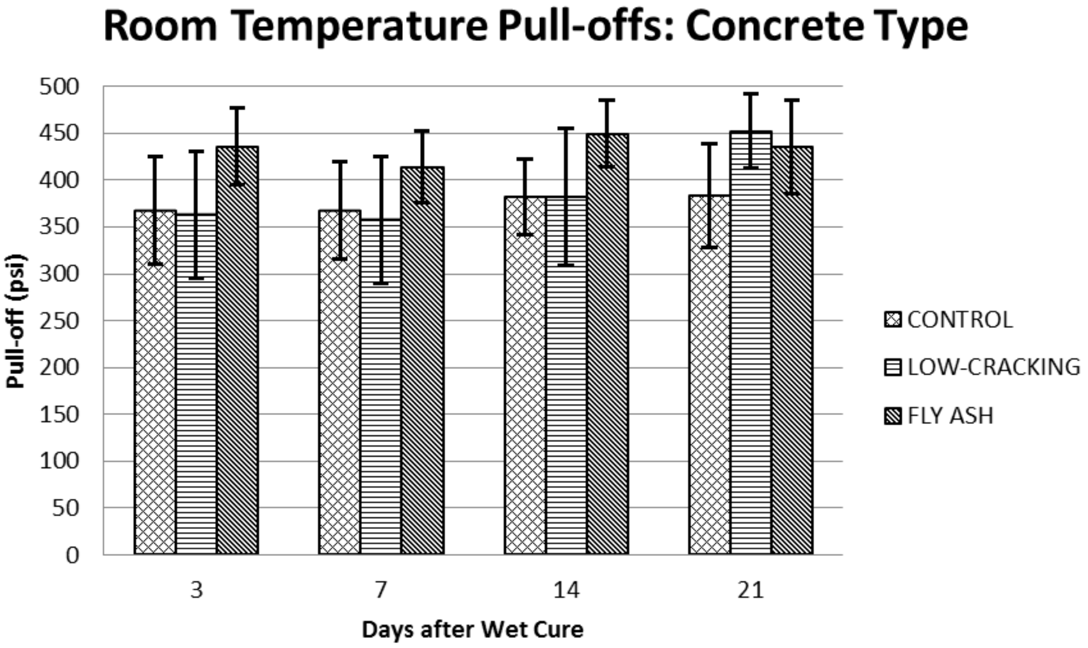

Figure 5.8: Average of Room Temperature Pull-Offs Based on Concrete Type

Instead of separating the results by concrete type, Figure 5.9 and Figure 5.10 categorize the results by the temperature at which the slabs were wet cured: 40°F, 73°F, and 100°F. Different temperatures during initial hardening of the concrete result in different crystalline structures within the concrete. Moisture within these concretes also can vary depending on the wet cure temperature. In Figure 5.9, the 100°F wet cured slabs produced the highest pull-off strengths and consistently had lower moisture readings than the 40°F or the 73°F cured slabs. Moisture could be affecting these results, especially at the 3- or 7-day drying times when moisture readings are highest. Figure 5.10 shows room temperature pull-off tests for the various wet cure temperatures. These results are more consistent across the drying times, but the 73°F slabs generally produced lower pull-off results. Moisture readings from the 73°F slabs were consistently higher than the 40°F or 100°F slabs. Lower pull-off test results could be the result of increased water vapor pressure forming at the bond interface. Each bar in Figure 5.9 and Figure 5.10 represent 15 slabs or 60 pull-off tests.

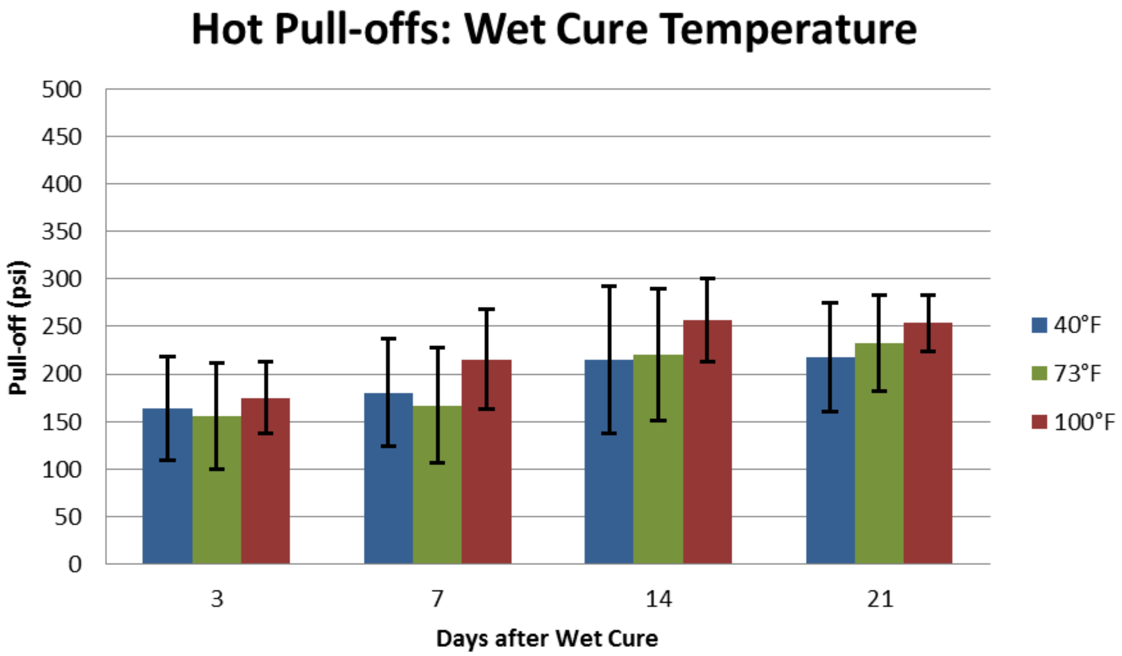

Figure 5.9: Average of Hot Pull-Offs Based on Wet Cure Temperature

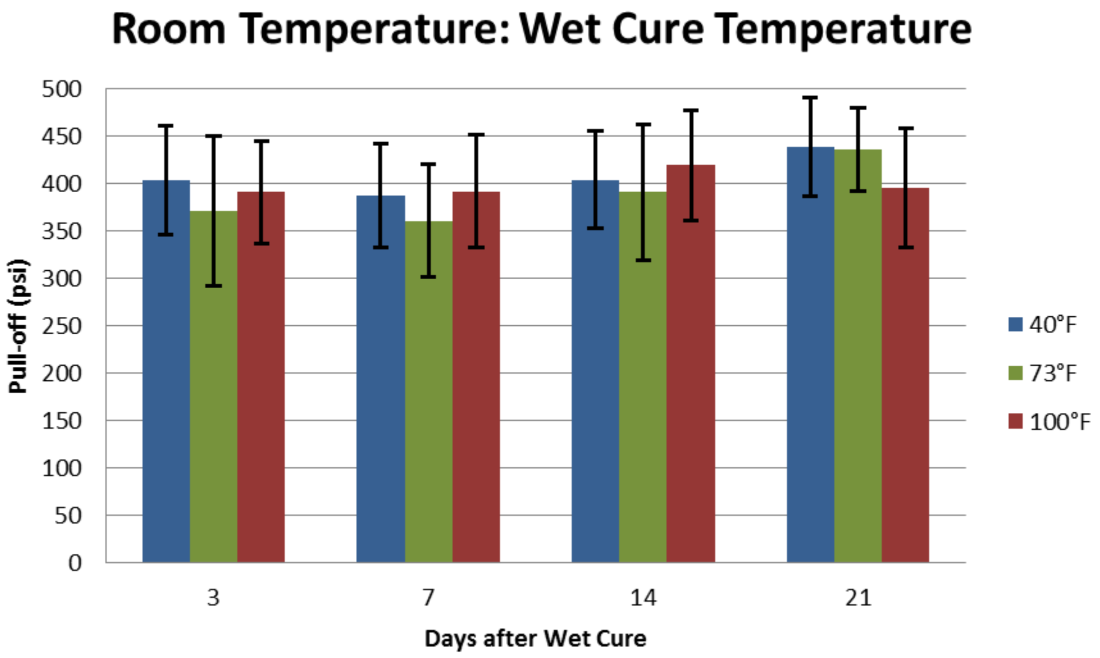

Figure 5.10: Average of Room Temperature Pull-Offs Based on Wet Cure Temperature

Pull-off test results can also be separated by the epoxy-polymer overlay system used. Similar to Figure 5.9, Figure 5.11 shows all test results with respect to the amount of drying time. The drying time results are then split between the epoxy-polymer overlay systems. Each bar in both Figure 5.11 and Figure 5.12 is the average of nine slabs or 36 pull-off tests. As seen previously in other pull-off test figures, results generally increase as the length of drying increases. By Day 21, four out of five epoxies averaged approximately 250 psi. Only Epoxy 1 fell below 200 psi on Day 21 and Epoxy 1's results show the lowest pull-off tests for all four dry curing times. In the room temperature pull-offs, Epoxy 1 again produces the lowest pull-offs for both the 3 and 7 days before eventually producing the highest average at 21 days. Epoxy 4 consistently had one of the highest pull-off averages in both the hot and room temperature pull-offs for all four drying times.

Full results on pull-off tests can be found in Appendix C.

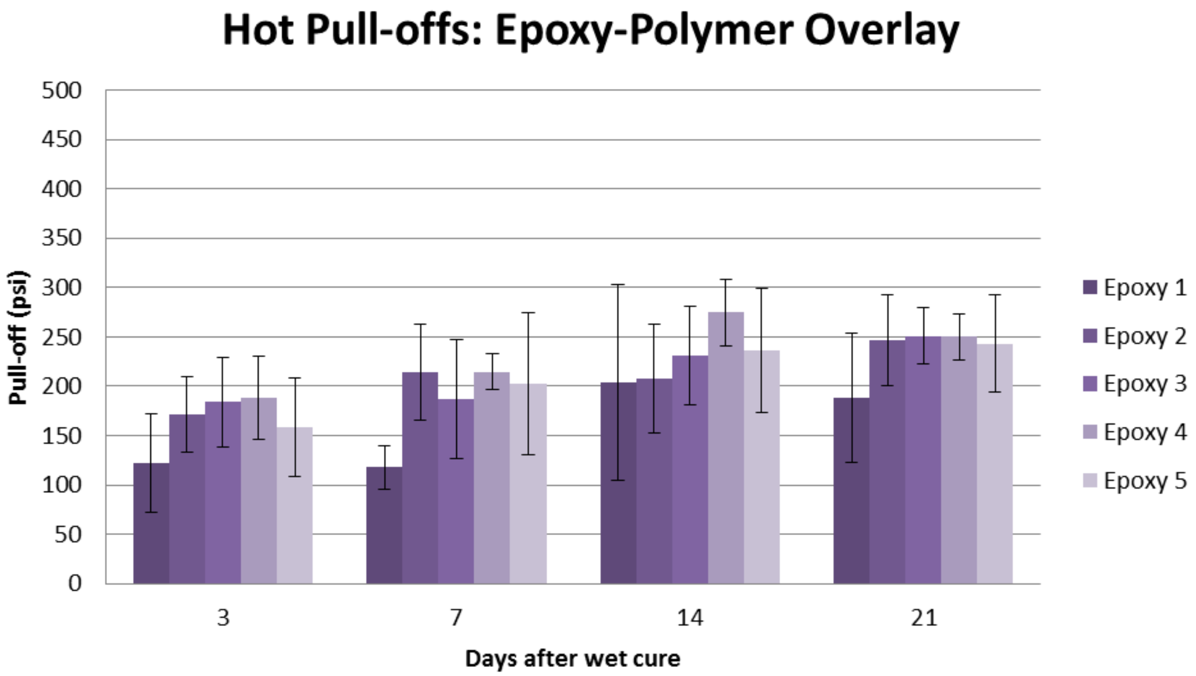

Figure 5.11: Average of Hot Pull-Offs Based on Epoxy-Polymer Overlay System Used

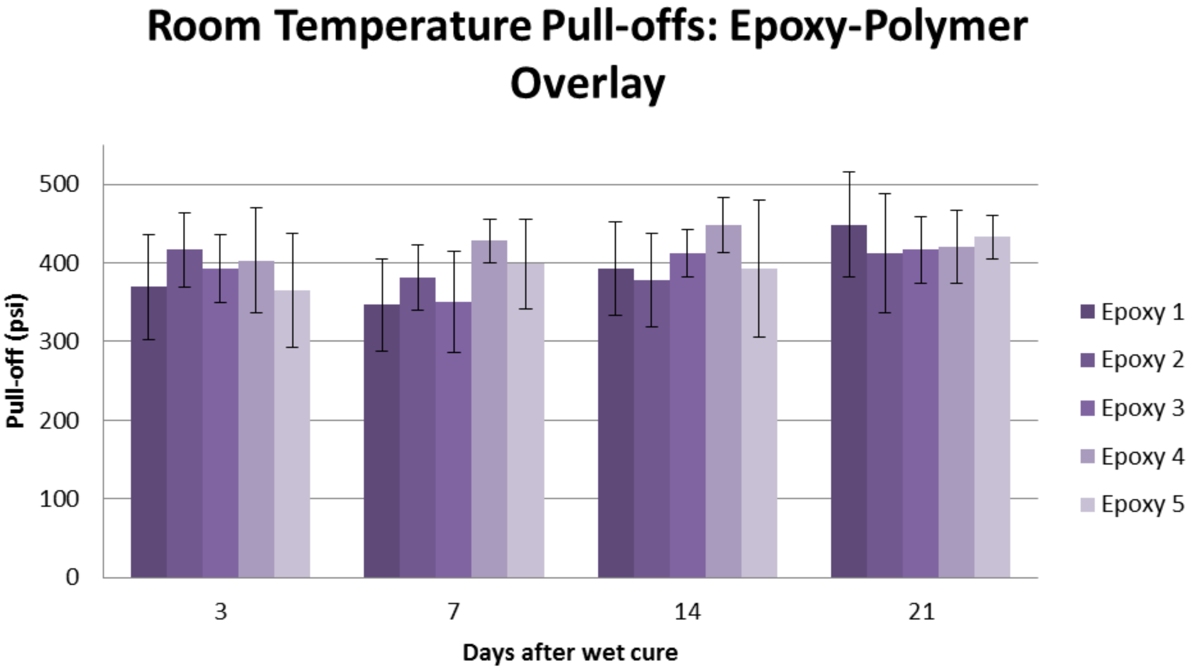

Figure 5.12: Average of Room Temperature Pull-Offs Based on Epoxy-Polymer Overlay System Used

After looking into both the moisture meter results and the pull-off test results, both results can be compared directly. Figure 5.5 showed the moisture meter results for fly ash concrete slabs prior to sandblasting the surface. The results showed much higher moisture contents in the 73°F slabs for both the 3- and 7-day tests than in the 40°F and 100°F slabs. It would be expected that higher moisture readings would result in lower pull-off test results. To see if this would be true, the results of the pull-off tests corresponding to those same slabs shown in Figure 5.5 are shown in Figure 5.13 for the pull-offs conducted at the hot temperature and Figure 5.14 for the pull-off tests conducted at room temperature. The results for both the hot and room temperature pull-off tests do not show the 73°F pull-off results any lower than either the 40°F or 100°F results for the 3 and 7 day times. The 73°F fly ash slabs had an average moisture reading of 5.82%, yet still had higher average pull-off strength than the 40°F fly ash slabs that average a 3.44% moisture reading. To further investigate these findings, further testing was set up and can be found in Chapter 6. Smaller concrete specimens were cast to test the difference between the moisture meter readings and the actual moisture content within the concrete.

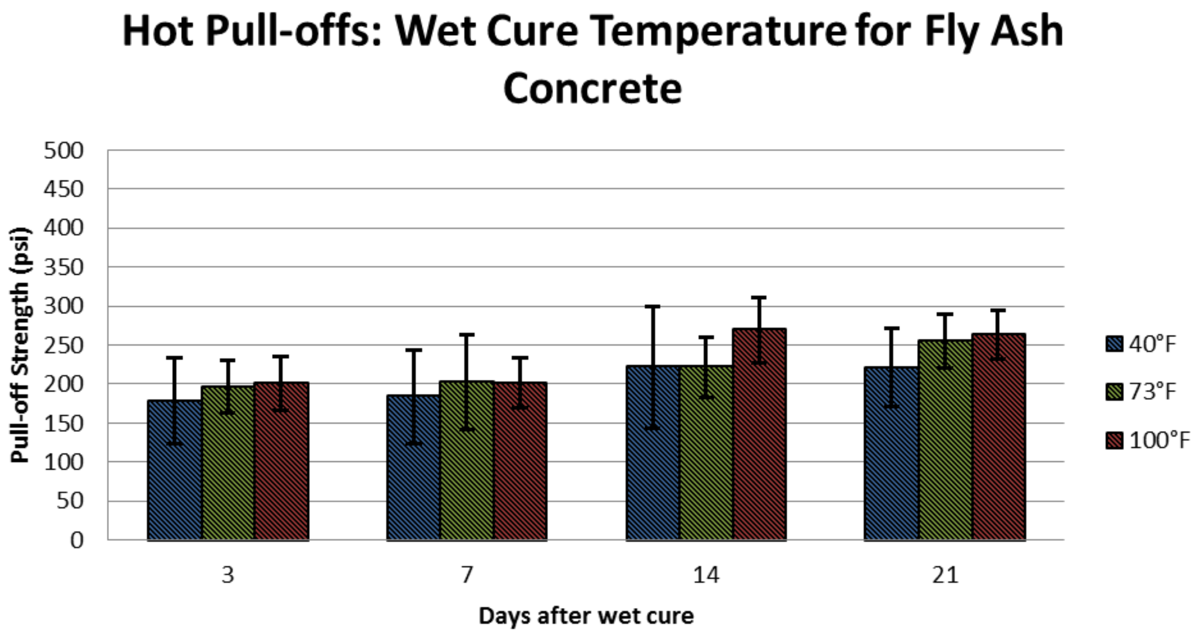

Figure 5.13: Hot Pull-Off Test Results for Fly Ash Concrete Slabs Split by Wet Cure Temperature

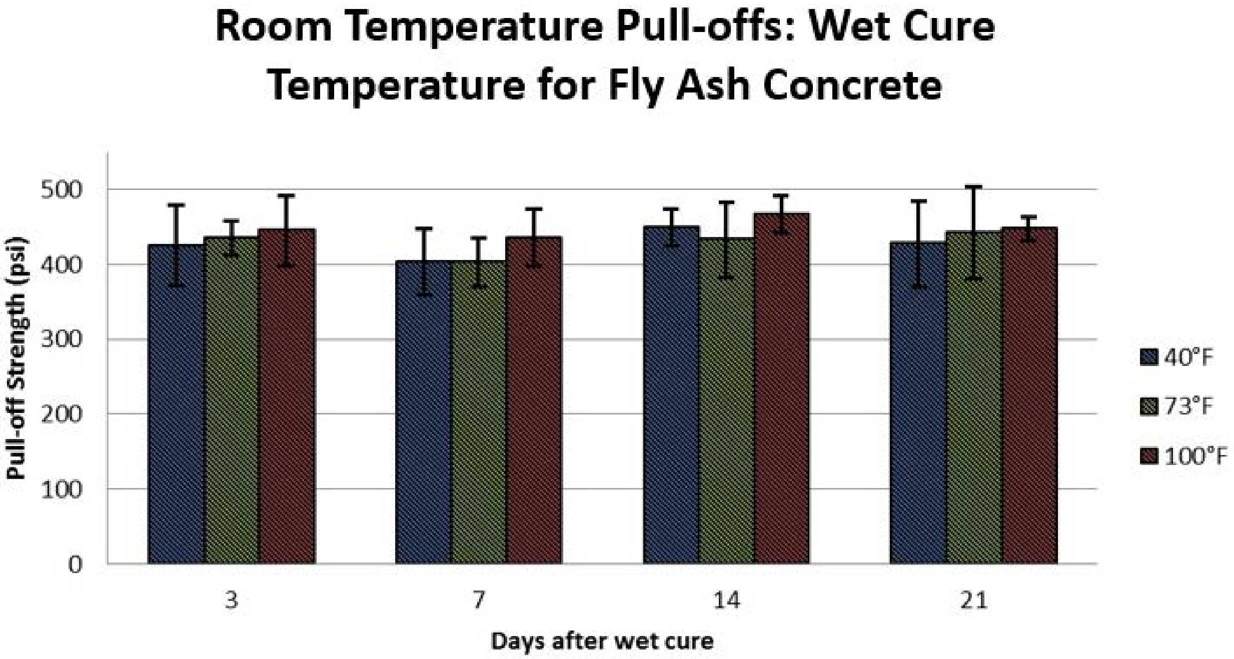

Figure 5.14: Room Temperature Pull-Off Test Results for Fly Ash Concrete Slabs Split by Wet Cure Temperature

5.2.1 Pull-Off Test Results Compared to Moisture Readings

Increased moisture content in the concrete slabs should result in lower pull-off test results. In an attempt to show this relationship, scatter plots were made as shown in Figure 5.15 and Figure 5.16. Figure 5.15 plots the pull-off test results conducted at 122°F against the average moisture readings, while Figure 5.16 plots the pull-off test results performed at 73°F against the average moisture readings. No correlation can be seen as the data points are all clumped together. The moisture readings mostly read between 3.0-4.0%, with the pull-off test results varying by over 200 psi. The surface moisture readings do not provide a good representation of the moisture content within the slab and thus the relationship between the pull-off tests and moisture readings do not correlate.

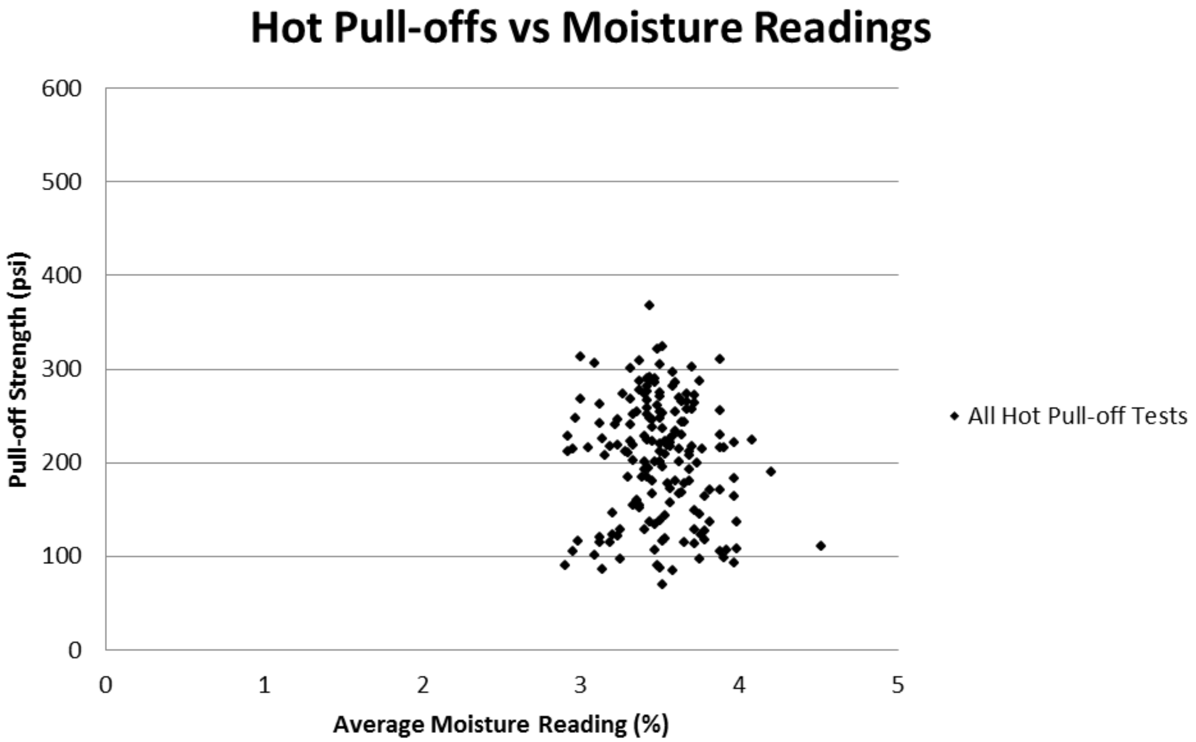

Figure 5.15: Hot Pull-Offs vs Moisture Readings

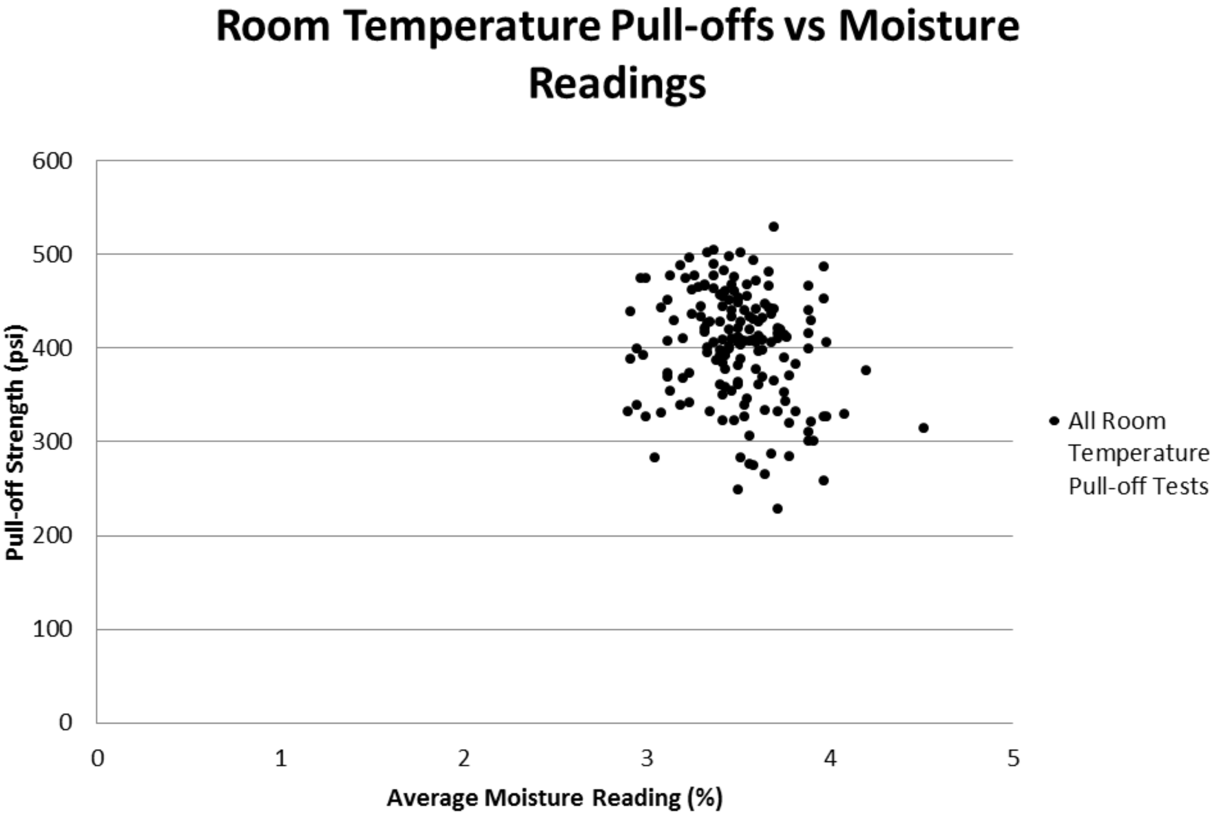

Figure 5.16: Room Temperature Pull-Offs vs Moisture Readings

5.2.2 Pull-Off Failure Type Results

Failure type for each pull-off test was recorded. Failure location is defined as the weakest point between the concrete and overlay. A majority of failures were Types 1, 2, or 3. A Type 1 failure occurs deeper than 0.25 inches in the concrete, and a failure at this location at a strength less than 250 psi is seen as weak concrete. A failure greater than 250 psi is expected when other failure types do not occur. Tensile strength in concrete ranges from 450 to 600 psi. As long as other failure types do not occur, the concrete will break here. A Type 2 failure also occurs in the concrete, but at a depth of less than 0.25 inches. A shallow failure in the concrete is caused by a weak top layer of concrete. Failure Type 3 indicates a bond failure at the concrete/overlay interface resulting from poor surface preparation or a buildup of water vapor pressure underneath the overlay. Type 4 and 5 failures are rare as long as the overlay and epoxy adhesive are mixed, placed, and cured correctly (KT-70, 2014).

The occurrence of each failure type was graphed, and the graphs were divided between the three concrete types. Figure 5.17 through Figure 5.19 show results for the failure type analysis. The failure type corresponds well to average pull-off strength for hot pull-off tests. The low-cracking concrete had the most Type 3 failures and the lowest average pull-off tests, as shown in Figure 5.7. The fly ash concrete contained the least amount of Type 3 failures and produced the highest average pull-off tests, also demonstrated in Figure 5.7. Results indicate that Type 3 failures produce weaker pull-off tests than failure Types 1 or 2. The new concrete could potentially cause weaker bond strength.

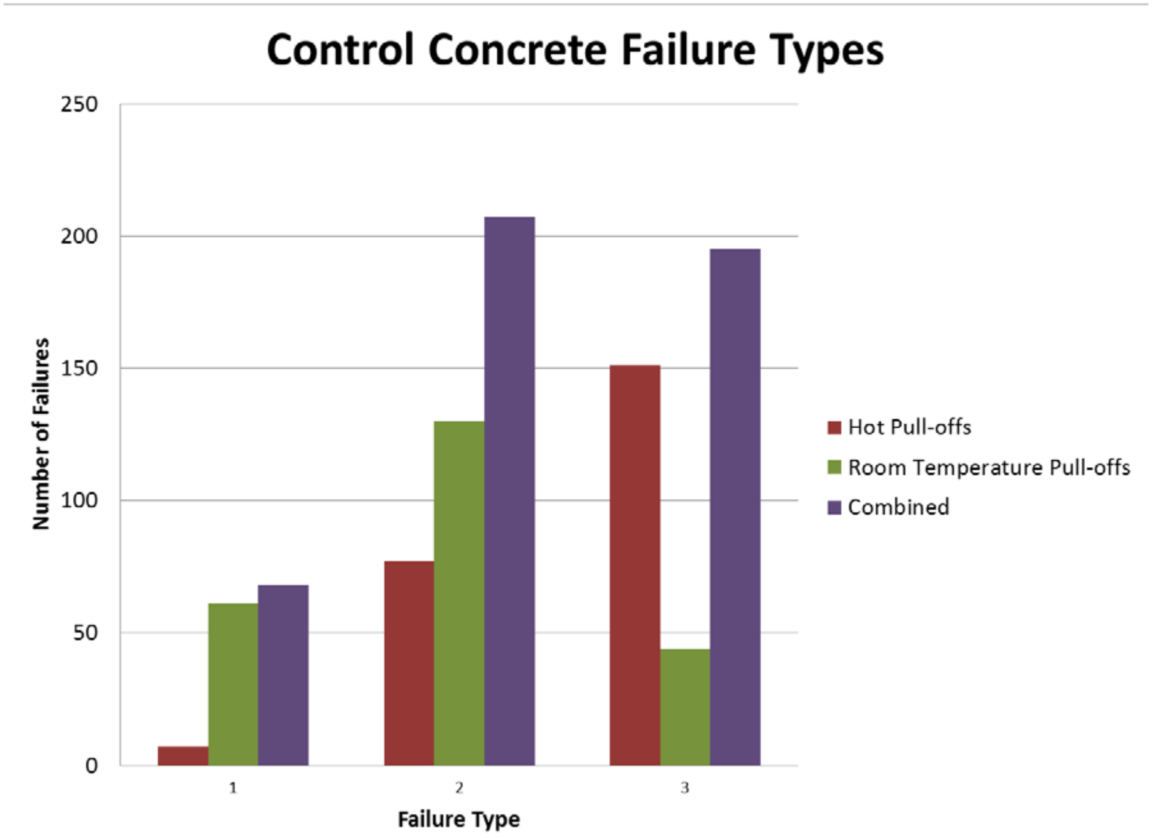

Figure 5.17: Control Concrete Failure Types

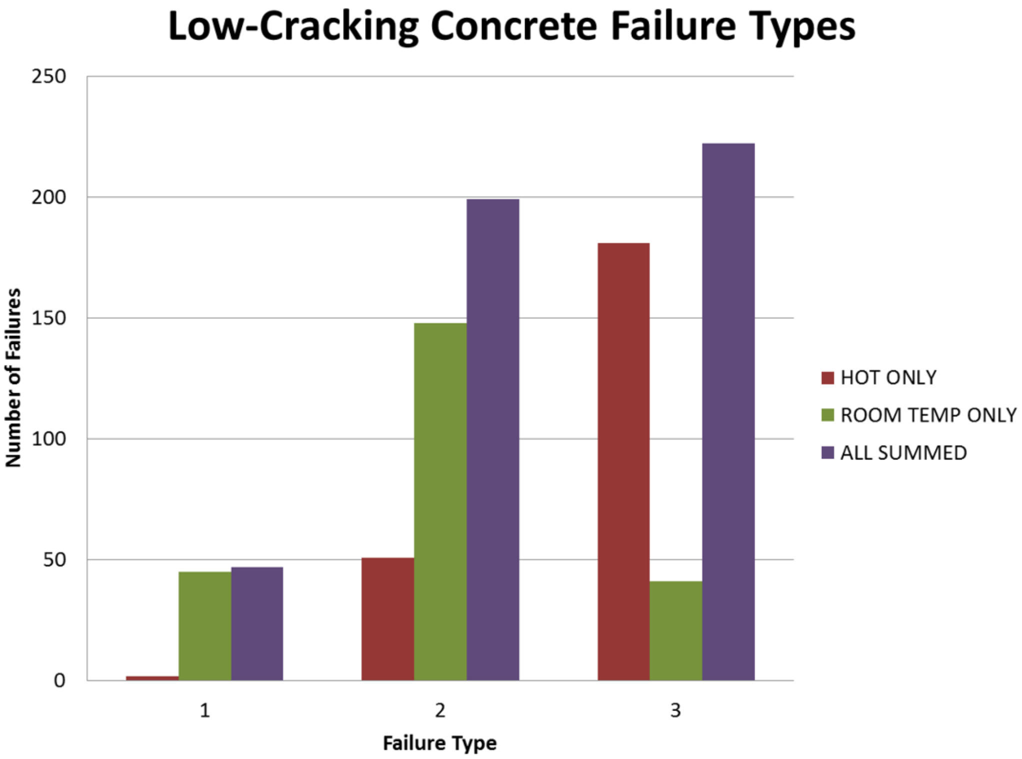

Figure 5.18: Low-Cracking Concrete Failure Types

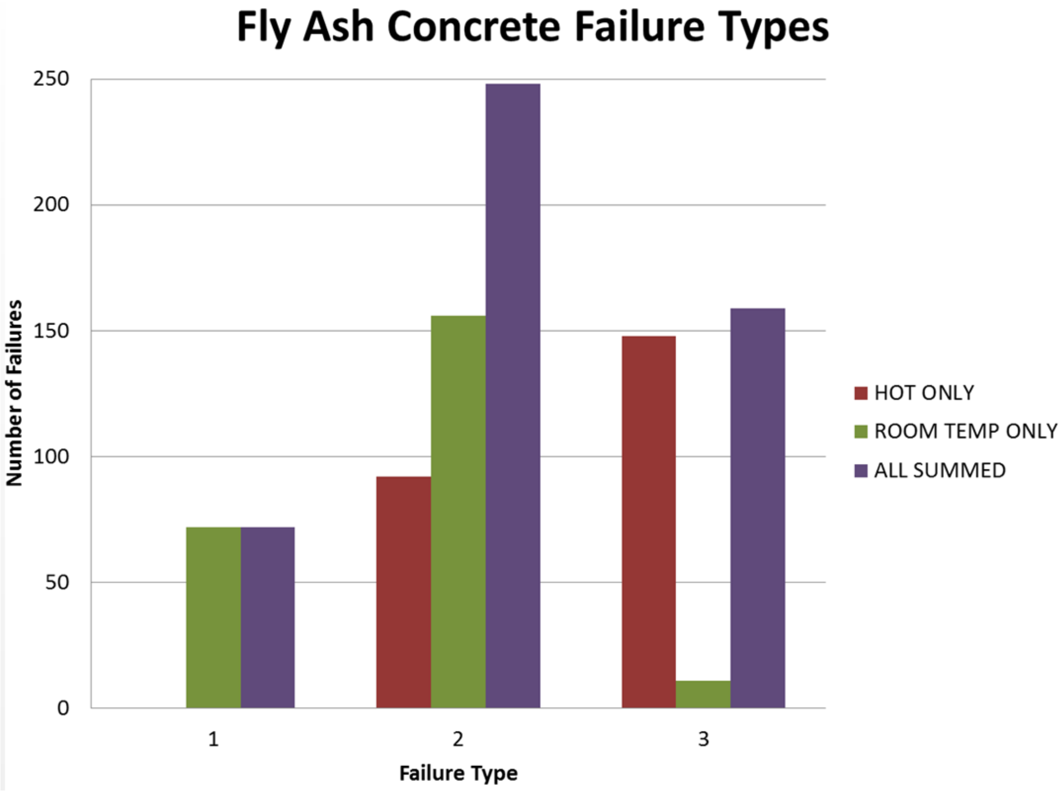

Figure 5.19: Fly Ash Concrete Failure Types

Further analysis of failure types confirms that Type 3 failures produce weaker pull-off strengths. Analysis performed showing the failure types corresponding to the different wet cure temperatures further show that Type 3 failures produce weaker pull-off strengths. On average, the 100°F slabs produced less Type 3 failures, more Type 1 and 2 failures, and higher pull-off tests than the 40°F and 73°F tests. All data and figures for this analysis are presented in Appendix D.

5.3 Concrete Compressive Strengths

Concrete compressive strengths were found for the slabs upon completion of wet curing and when the pull-off tests were performed. The compressive strengths at the time of the pull-off test did show some correlation to the pull-off tests conducted at room temperature. This can be attributed to the failure types. The vast majority of failures for the room temperature pull-off tests were in the concrete. If the concrete has more strength, then the pull-off test should reach a higher strength.

Figure 5.20 shows the compressive strengths of the concrete as the pull-off tests were being conducted. The results are split by the amount of days the cylinders were allowed to dry and the type of concrete they consisted of. For the most part, not much strength was gained from the 3-day (17 days after batching) to the 21-day (35 days after batching) tests. What can be deciphered from this Figure is the relationship between the cylinder strength and the pull-off test. Comparing Figure 5.20 with the pull-off tests performed at the hot temperature (Figure 5.7), almost no correlation can be found. This is due to the majority of pull-offs occurring as a Type 3 or at the bond interface. The concrete strength has no impact on the results of pull-off tests that fail at the bond interface. If Figure 5.20 is compared with the results from the pull-off tests conducted at room temperature (Figure 5.8), then a few observations can be made. First, the fly ash concrete compressive strengths are the highest for each time period. The fly ash slab pull-off results are consistently the highest too. On the other side, the control concrete slabs are at the bottom of both the compressive strengths and pull-off test results.

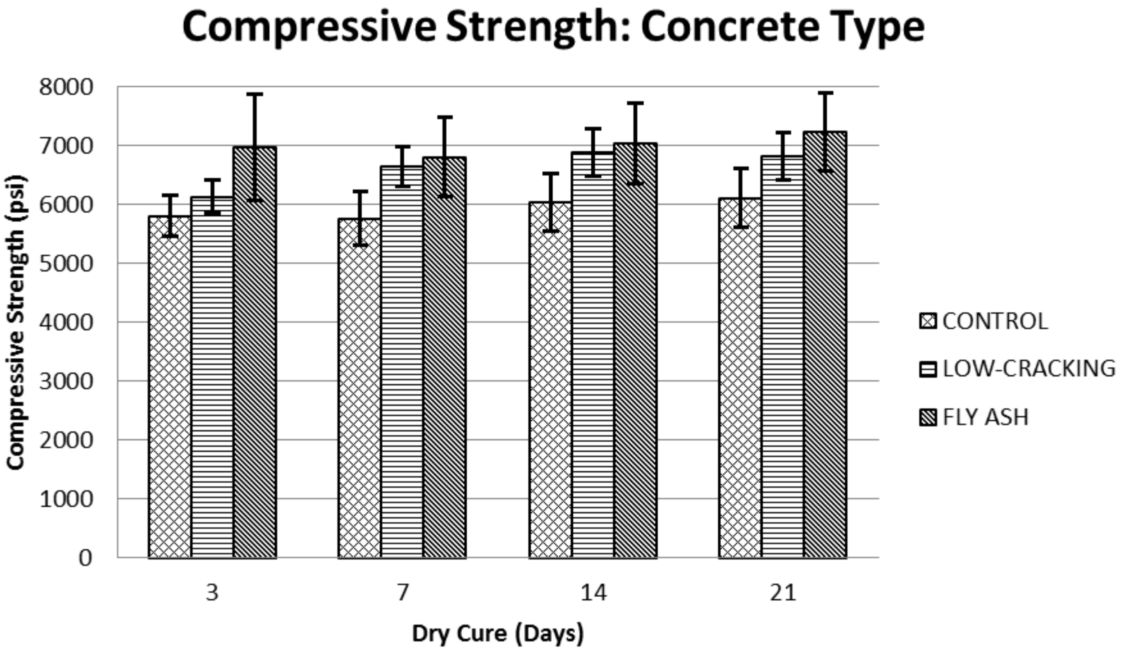

Figure 5.20: Compressive Strength of Concrete by Concrete Type

Looking at the compressive strengths divided by their wet cure temperature instead of their concrete type, we can again see some correlation. Figure 5.21 shows the compressive strengths split by the time allowed to dry and the temperature of their wet cure location. A comparison of these results to the pull-off results taken at the hot temperature (Figure 5.9) shows no correlation because many of the results were at the bond interface. Instead compare it to the pull-off tests conducted at room temperature and split between wet cure temperatures (Figure 5.10). To find correlation, each temperature must be looked at separately. The 40°F compressive strengths consistently gain each time period. The pull-off results show this consistent gain between the 7- and 21-day times, but the 3-day results are higher than expected. The 73°F compressive strengths actually decrease slightly from 3 to 7 days before gaining strength through the 14 and 21 days. This trend is reflected in the pull-off results. The pull-off results decrease from the 3-day to the 7-day results before gaining strength. Finally, the 100°F pull-off results seen in Figure 5.10 show the 14-day pull-off results as being the highest and the 21-day results dipping a little. The compressive strengths for the 100°F cylinders reflect this behavior. The 14-day results are higher than the 21-day results.

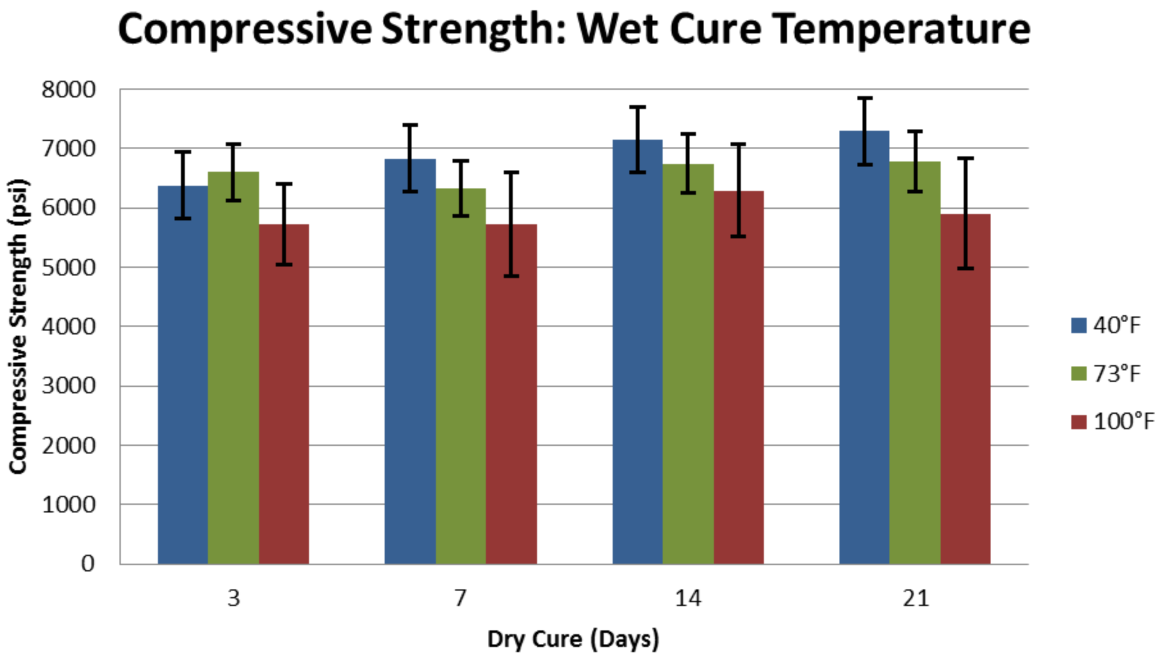

Figure 5.21: Compressive Strength of Concrete by Wet Cure Temperature

The differing wet cure temperatures do not show that a higher compressive strength will result in a higher pull-off test when compared relative to each other. The compressive strengths for the specimens cured at 100°F were the lowest between the wet cure temperatures by a significant amount for each drying time, but sometimes had the highest pull-off test results. This could be the result of the wet cure temperature's effect on the concrete's mechanical properties. Differing wet cure temperatures can result in a different tensile strength relative to its compressive strength.

All compressive strength results can be found in Appendix B.

Chapter 6: Additional Testing

Questions arose during the slab testing that required special attention. The moisture meter consistently provided varying moisture readings, but is variation expected and to what degree? Were the readings accurate? A large difference of at least 150 psi between the hot and room temperature pull-off tests was also noted. Either water vapor pressure caused the difference or the epoxy softened when heated. Tests were developed for this study to answer these concerns and questions.

6.1 Moisture Readings Taken Over Full Drying Time

Moisture readings during the main testing procedure were conducted on slabs only after the slabs had finished dry curing, and these readings provided only single data points on a timeline progression. Moisture readings could indicate lower moisture content in a 3-day dried slab but higher moisture content on a similar 7-day dried slab. In order to see time progression of the moisture content from start to finish, a few slabs were selected to have moisture readings taken periodically throughout their drying time. The selected slabs included several sets of 21-day dried slabs containing fly ash. Results of this test are shown in Figure 6.1. Complete results containing individual moisture meter readings are presented in Appendix E.

As demonstrated in Figure 6.1, the 40°F and 73°F sets of slabs emerged from their wet cure at or near the 6.9% maximum moisture reading. The 100°F slabs gave moisture readings near 4.0%. All slabs converged to an average moisture reading near 4.0% after 10 days.

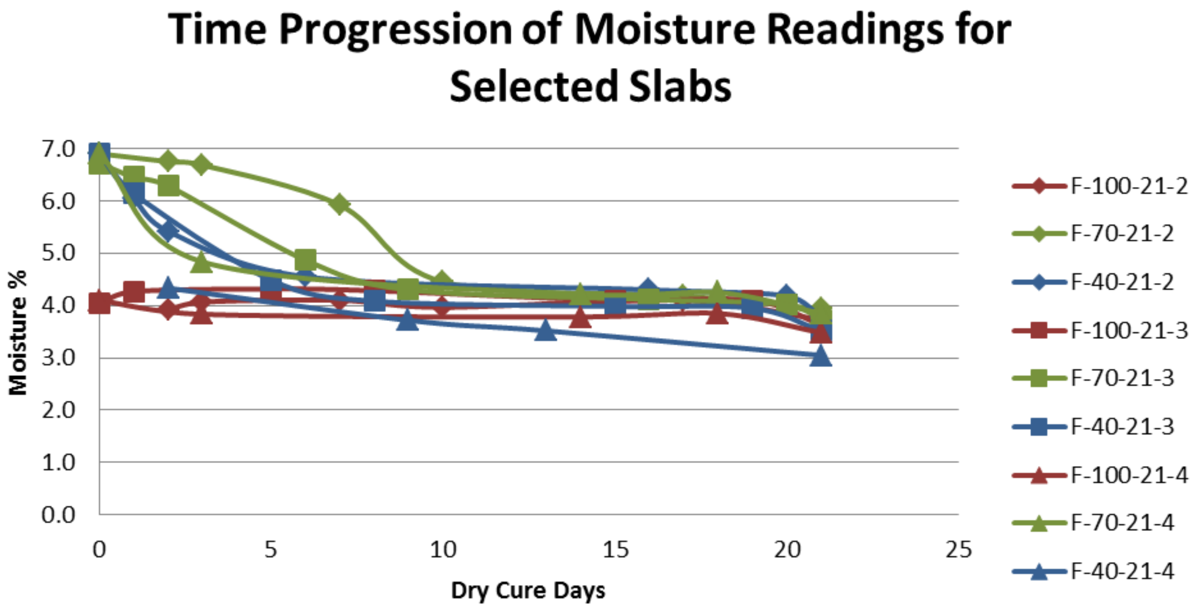

Figure 6.1: Time Progression of Moisture Readings for Selected Slabs

6.2 Moisture Meter Accuracy

During testing, speculation arose as to whether the moisture meter was providing accurate results because many results collected within the same zone gave varying results. Maximum moisture content within each zone was the recorded value in an effort to produce consistent results.

Test specimens were developed and sized to test their moisture content by using the moisture meter or oven for drying. Specimen sizes were 4×16×3 inches deep, as shown in Figure 6.2. Surface area of the specimens represented the size of a zone used when measuring moisture in the slabs in the main testing for this study. Three readings were taken on each specimen: one on each end and a third in the center.

Figure 6.2: Test Specimen Cast to Test Moisture Content

Specimens were cast for two conditions. The first variable included dry curing at 73°F and 50% relative humidity or heat dried in an oven at 200°F so that all moisture escaped the slab. The second variable tested the effectiveness of wrapping the specimen in plastic. All slabs to be overlaid had their bottom and sides wrapped in plastic between wet and dry curing, as described in Chapter 4. The primary goal was to simulate slab encasement in a larger slab so that moisture was unable to escape from the sides and bottom of the slab. For the moisture to escape from within the concrete, it would be forced to travel up through the surface. In this test, half of the specimens were wrapped in plastic in the same manner as the slabs and the other half of the specimens were not wrapped. As drying occurred, the specimens were tested for moisture content using the moisture meter and weighed to determine the weight of moisture lost. Four bars were made for this test. Bar 1 was dried and not wrapped. Bar 2 was heat dried and not wrapped. Bar 3 was dried and wrapped. Bar 4 was heat dried and wrapped.

Moisture readings for each of the four slabs are presented in Figure 6.3 through Figure 6.6. The three different series in each Figure show moisture readings for three locations from which a reading was taken on each specimen. Each Figure shows moisture readings through 150 hours (Day 7) after wet cure. After this point, all moisture readings from each specimen converged. Specimen 1 and 3 were dried, but Specimen 3 was wrapped in plastic while Specimen 1 was not wrapped. Moisture readings for Specimen 1 showed two out of three readings converged to approximately 4.0% after only 20 hours. The third reading took approximately 100 hours to converge to 4.0%. Specimen 3 demonstrated variability in readings because 100 hours were required for two out of three readings to converge to 4.0%, and approximately 160 hours for all three readings. The additional time required for Specimen 3 could be a result of the plastic wrap on the bottom and sides of the concrete, which prevented moisture from evaporating. Moisture could only escape through the surface. These results show that the plastic wrap performed as expected in its simulation of the specimen being a part of a much larger slab. Inconsistency in some moisture reading progressions was also observed for Specimens 1 and 3. Some moisture reading progressions demonstrated an increase from one reading to the next, specifically in the first 40 hours of dry curing as seen in Figure 6.3. The conclusion was made that the moisture meter is not consistently able to provide the maximum value of moisture in each section with only one reading; multiple readings must be taken and the maximum reading should be recorded to ensure consistency. Some moisture readings from the slabs to be overlaid demonstrated lower than the actual moisture because insufficient readings were taken.

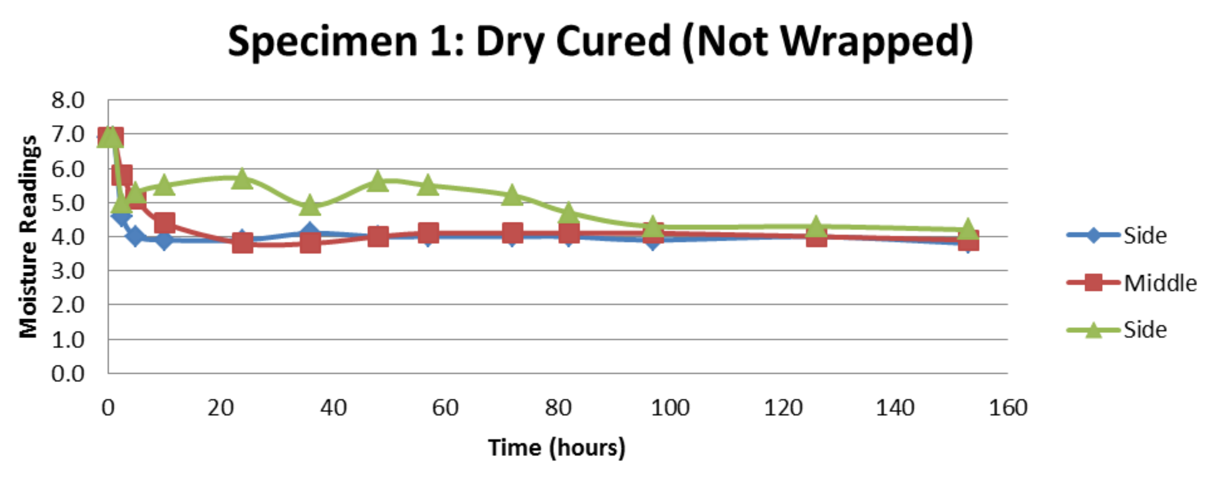

Figure 6.3: Specimen 1: Dried (Not Wrapped)

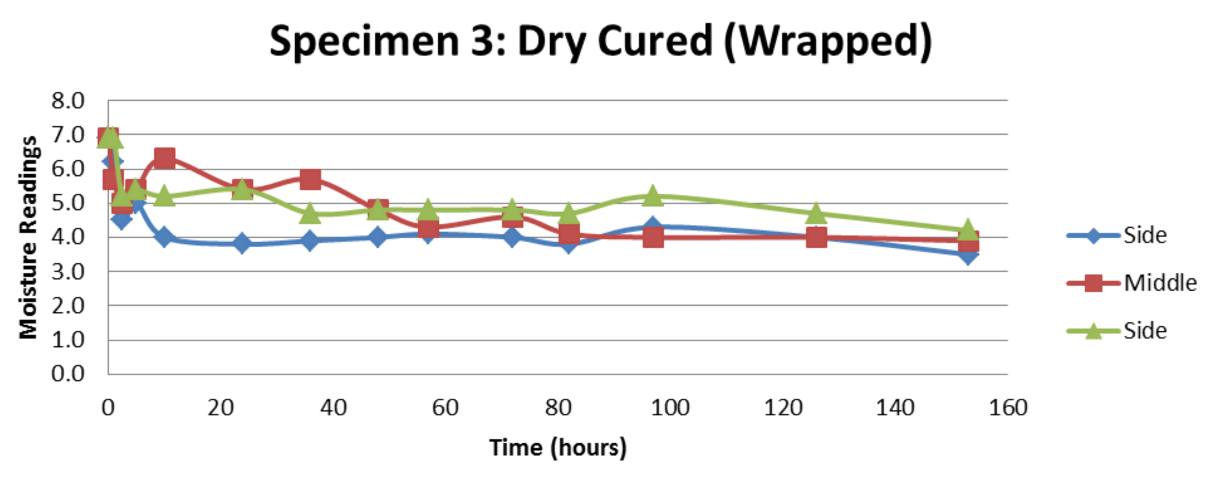

Figure 6.4: Specimen 3: Dried (Wrapped)

Specimen 2 and 4 were heat dried. Directly after wet curing, one specimen was similarly wrapped in plastic as Specimen 3 and the other specimen was not wrapped. Both specimens were placed in an oven at 200°F for 160 hours until they were completely dry. The moisture content was tested by measuring the weight of each specimen. When the weight of the specimen no longer decreased, then all moisture had been extracted. Results indicate that wrapping Specimen 4 in plastic had no effect on the drying process because both specimens demonstrated similar drying patterns. The specimens dried quickly within the first 10 hours, before a slower rate of moisture loss was established. Moisture readings show that this initial moisture loss declined from 6.9% (moisture meter maximum reading) to 3.0-3.5%, and then only minimal moisture loss occurred until approximately 50-60 hours. A probable cause of this stagnation could be that internal moisture of the specimen slowly reached the surface and replenished surface moisture at the same rate of evaporation. After approximately 60 hours, the specimens continued to dry at an increased rate until moisture readings were less than 1.0%. Figure 6.5 and Figure 6.6 show results of Specimen 2 and 4 respectively.

Differences in moisture content of moisture meter readings and moisture percentage calculated by specimen weight are shown in Figure 6.7. Average moisture meter readings for Specimens 2 and 4 from Figure 6.5 and Figure 6.6 and the moisture percentage in the entire specimen based on the weight loss of the specimen while heat drying are included. The moisture readings leveled out between 10 and 60 hours of drying, similar to Figure 6.5 and 6.6. The moisture percentage based on weight continued to decrease during this same timespan because the moisture percentage accounts for the entire specimen, while the moisture meter only measures the surface of each specimen. This also indicates that as the specimen dries out, moisture from within the specimen escapes through the surface. The surface, therefore, has higher moisture content than the overall moisture within the slab for the first 100 hours of drying.

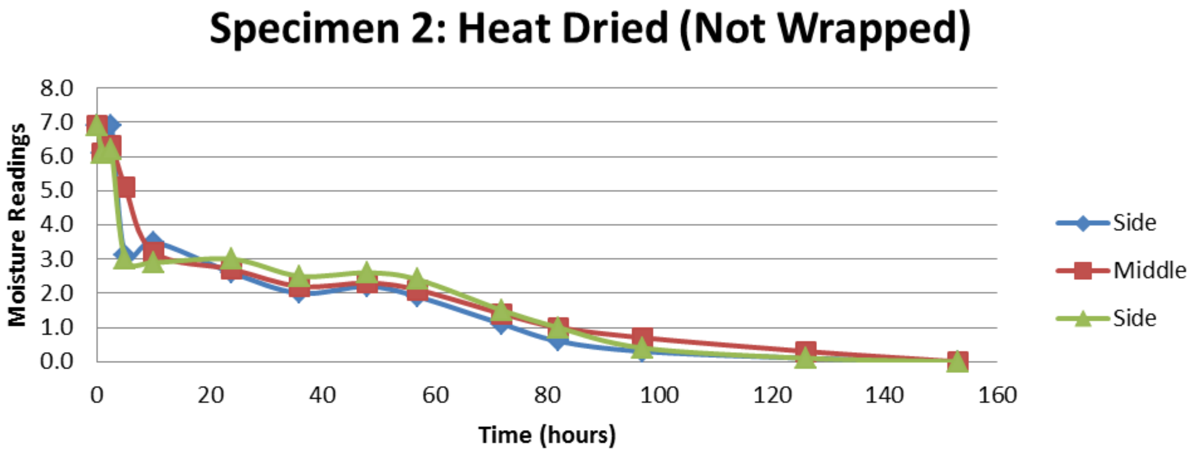

Figure 6.5: Specimen 2: Heat Dried (Not Wrapped)

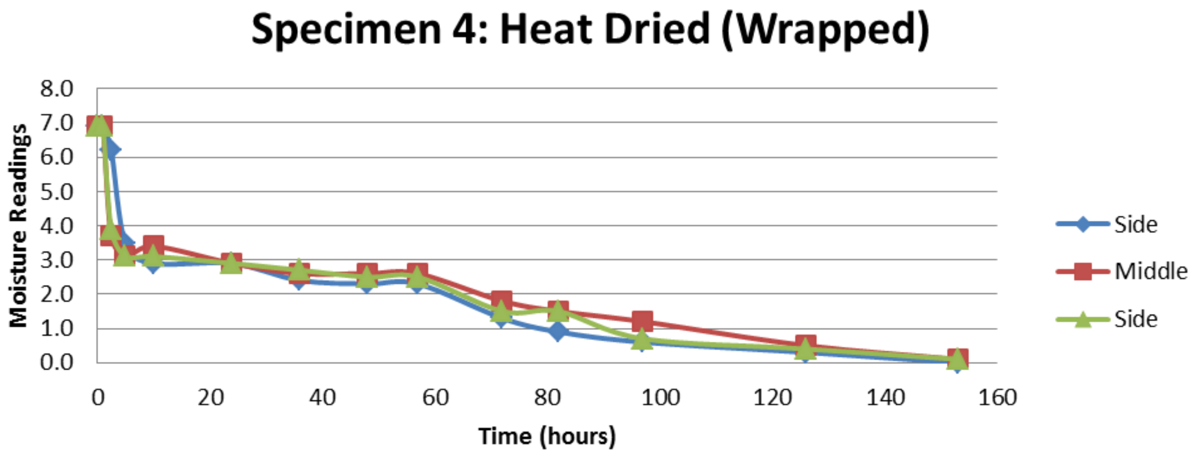

Figure 6.6: Specimen 4: Heat Dried (Wrapped)

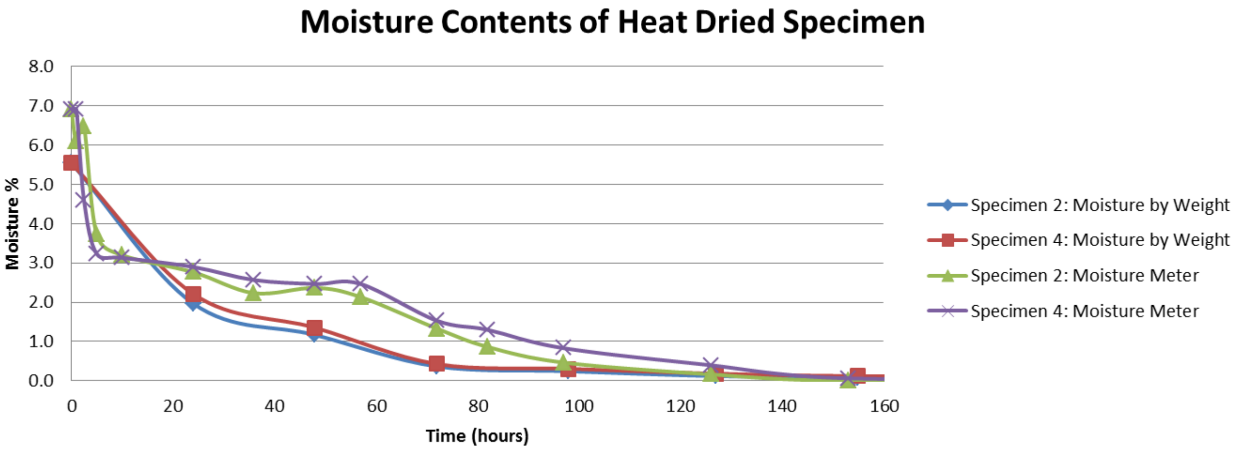

Figure 6.7: Moisture Content of Heat Dried Specimen

6.3 Epoxy Tensile Test

Based on pull-off test results, tests conducted at room temperature performed much better than tests performed directly after heating the slabs to 122 to 125°F. Two potential causes were identified. The first cause could have been that the increased temperature on an epoxy polymer overlay on new concrete caused water vapor pressure, consequently encouraging overlay delamination. Overlay delamination due to water vapor pressure was a main focus for this study because water vapor pressure is a major concern with new concrete. The other potential cause could have been the loss of tensile and bond strength in the polymer overlay system as temperature increased. Increased temperature increases the epoxy's plasticity, causing the epoxy to lose strength. A direct tensile test was set up to determine if temperature increase caused the lower bond strengths.

A direct tensile test was developed to remove the potential for failure due to water vapor pressure or weak concrete. Two aluminum pucks were epoxied together using a slurry with flint aggregate. This allowed failure to occur in the epoxy or at the interface between the epoxy and aluminum puck. Figure 6.8 shows the two epoxied pucks. The bottom puck was wrapped in Gorilla tape to fill voids in the forms so epoxy would not ooze out between the pucks. The epoxy hardened for 24 hours and then half of the epoxied pucks (five) were placed in an oven at 122°F and half the epoxied pucks (five) were kept at room temperature (~73°F). The epoxied pucks were allowed to heat up and maintain heat for an additional 24 hours.

Figure 6.8: Two Aluminum Pucks Epoxied Together

The testing setup for direct tension is shown in Figure 6.9. A metal loop was screwed into both pucks and the connections created a pinned connection, allowing the test to be in direct tension. Utilization of a fixed connection would have produced an eccentricity since the pucks never came out perfectly aligned, the two pucks were separated at a rate of 60 lbf per second or approximately 20 psi/second. Results for both pucks kept at room temperature and pucks kept at 122°F are presented in Table 6.1. Temperatures for the heated pucks were recorded. The pucks were between 121-122°F when removed from the oven. By the time they were mounted in the testing apparatus, they had fallen to a temperature between 105-110°F and remained in that range for the duration of the test. After removing results that full coverage of the epoxy on the puck was not achieved, the 73°F tests averaged a force of 2,948 lbf (938 psi), while the 105-110°F tests averaged 2,827 lbf (900 psi). With bond strengths to the aluminum pucks reaching over 900 psi for both the 73°F and the 105-110°F, the epoxy clearly bonds better than the pull-off tests show. It can be concluded that it is not the epoxy weakening at the higher temperature that is causing the approximately 200 psi average differences between the hot and room temperature pull-off test results. Instead, it is the water vapor pressure forming at the bond interface that is decreasing the pull-off strengths for the 122°F pull-off tests.

Figure 6.9: Epoxy Tensile Test Setup

Table 6.1: Epoxy Tensile Test Results

	Tensile Force			
	73°F		122°F	
	Force (lbf)	Comments	Force (lbf)	Comments
Test 1	3240		3127	
Test 2	2678		1644	Not full coverage
Test 3	2685	Not full coverage	2940	
Test 4	2855		2415	
Test 5	3018		-	Broke prior to testing
Average of all tests	2895		2532	
Average of tests with full coverage	2948		2827	

Chapter 7: Conclusions and Recommendations

7.1 Conclusions

Six conclusions can be made based off of the results of the moisture meter readings from both the slabs and the additional tests for the smaller concrete specimen.

1. Moisture readings from the concrete slabs generally decreased with more drying time. However, the amount of moisture decrease was very minimal when the readings were taken after sandblasting the surface. This is likely due to the sandblasting operation itself, as dry-compressed air was sprayed over the concrete surfaces which dried them out. The greatest average moisture reading decrease occurred between 7 and 14 days of drying as shown in Table 5.1.
2. The low-cracking concrete (the only concrete with 0.44 w/c ratio) and the 73°F both recorded slightly higher moisture contents than the other conditions for moisture readings taken after sandblasting.
3. Taking moisture readings prior to sandblasting proved to show a greater discrepancy between curing conditions and moisture content. For the fly ash concrete cured at 73°F, the moisture readings were far above both the 40°F and the 100°F cured slab moisture readings for both the 3- and 7-day drying times. By the 14-day drying time, the 73°F had converged with both 40°F and 100°F slabs. The 40°F and 100°F slab surfaces dried out much quicker than the 73°F slabs. The difference in moisture contents can be attributed to two causes. First, the 73°F slabs were wet cured in a room with mist being sprayed constantly, while the 40°F and 100°F slabs were both wet cured with burlap. The 73°F slabs were wet cured ideally, but the 40°F and the 100°F slabs may be more representative of curing an actual bridge deck. Second, both the 40°F and 100°F slabs experienced a temperature change. Upon completion of wet curing, they were moved to dry at 73°F. This temperature difference increased evaporation from the slabs.

4. Moisture readings taken on slabs periodically throughout their drying time of 21 days showed that both the 40°F and 73°F slabs began at or near the moisture meter’s maximum reading of 6.9%. Between Day 7 and 14, both the 40°F and 73°F slabs had converged to a moisture reading between 4.0-4.5%. The 100°F slabs, on the other hand, stayed relatively constant throughout the entire 21-day drying period. They began near 4.0% moisture and remained around 4.0% until dropping to 3.5% on Day 20.
5. Moisture readings taken on the smaller heat-dried specimen showed the difference between the surface moisture readings and the moisture content of the entire specimen. The heat-dried specimens lost a lot of moisture quickly before leveling out between 10 and 60 hours. The rate of moisture loss then sped up after 60 hours. The moisture content of the entire slab continued to drop at a faster rate than the surface moisture readings. This can be attributed to the internal moisture in the concrete. The surface readings indicated that the surface moisture is being replenished by the internal moisture, while the overall moisture content of the specimen decreases.
6. Also seen from the smaller specimen moisture tests is the effect plastic wrapping had on the concrete drying. The moisture readings were a bit more varied for the specimens wrapped in plastic when compared to the moisture readings for the specimens not wrapped. This is likely because the internal moisture was allowed to escape only through the top surface of the concrete of the wrapped specimens, and not uniformly on all sides, which led to increased variability.

Four conclusions from the pull-off test results are shown below.

1. Pull-off tests performed at 122°F resulted in nearly half the pull-off strength of the tests performed at room temperature, or 73°F ± 5°F. The room temperature pull-off test results were relatively consistent across the drying times. The drying time did not seem to affect the room temperature pull-off

tests much. The hot pull-off tests were affected by the drying time though. The results showed an increase in the hot pull-off test results when given more drying time. Maximum strength increase occurred between 7 and 14 days. The research suggests that the difference between the 122°F and 73°F pull-off tests may be due to vapor pressure at the bond interface. Additional testing showed that epoxy retained adhesion in excess of 900 psi while at an elevated temperature which is much larger than the hot pull-off test results.

2. The fly ash concrete performed the best for both the hot and room temperature pull-off tests. Also, the 100°F wet cured slabs produced the highest pull-off results at the hot temperature.
3. The moisture meter readings for the fly ash concrete slabs showed the 73°F slabs to have much higher moisture readings than either the 40°F or the 100°F slabs. The resulting pull-off tests for those same fly ash concrete slabs at 73°F were not lower as expected. With the results from the additional testing, it can be determined that the surface moisture readings are a poor indicator of the total moisture within the slab. Moisture from within the slab slowly seeps to the surface to replenish the surface moisture which aids in a lower pull-off strength.
4. Even though surface moisture readings for some slabs were very similar between slabs dried for 3 and 21 days, once the overlay was placed and heated to 122°F, more internal moisture was available to the 3 day slabs. The higher moisture content from within the slabs dried 3 days caused lower pull-off test results than those for the slabs dried for 21 days.

Three conclusions from the pull-off failure type results are shown below.

1. The majority of the hot pull-off tests were Type 3 while the majority of the room temperature pull-off tests were either Type 1 or Type 2.
2. Type 3 pull-off failures made up the majority of all pull-off tests for both the control and low-cracking concretes at both the 40°F and 73°F wet cure

temperatures. Type 2 pull-off failures were the majority in the fly ash concrete types and for the 100°F wet cure temperatures.

3. Higher pull-off strengths were recorded for both the fly ash concrete slabs and all the slabs wet cured at 100°F. This goes to show that pull-off failure Types 1 and 2 produce higher pull-off strengths than Type 3 failures.

Two conclusions were made based on the results of the cylinder compressive strengths.

1. The fly ash concrete produced the highest cylinder compressive strengths, and also the highest pull-off test results for both the hot and room temperature pull-off tests.
2. When comparing the compressive strengths of specimens with different wet cure temperatures, a higher compressive strength doesn’t always translate to higher pull-off results, as the different wet cure temperatures also result in different tensile strengths relative to their compressive strengths. However, for specimens with the same wet cure temperature, specimens with higher compressive strengths generally did have slightly higher pull-off values.

7.2 Implementation

From the previous conclusions, recommendations can be made for future placement of an epoxy-polymer overlay on a new bridge deck.

1. The time of overlay placement after wet cure could be reduced to 14 days and possibly to 10 days from the 21 days currently in place based on moisture content measurements.
2. The results from this research program indicate that pull-off test values for an epoxy-polymer overlay will be significantly reduced if the tests are conducted when the slab is hot. Therefore, it is recommended that pull-off tests be conducted during the coolest part of the day in order to obtain the best information about the quality of the overlay installation.

3. Surface moisture readings did not always give an accurate depiction of what the pull-off strength would do. A moisture test or moisture meter that can accurately measure moisture content of the slab deeper than just at the surface would be beneficial.
4. Future testing should be conducted to determine the effect that internal moisture content has on the pull-off strengths of polymer overlays. Moisture readings could be taken at different depths in the concrete to determine their effects on the vapor pressure and corresponding overlay bond.

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