ABSTRACT

Title of Thesis:	THE INFLUENCE OF SURFACE PREPARATION ON BOND STRENGTH BETWEEN CONCRETE OVERLAY AND UNDERLAY IN PRESTRESSED SLAB BRIDGES
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The objectives of this research were to experimentally study the influence of surface preparation on bond strength between concrete overlay and underlay in pre-stressed slab bridges and to explore the best practice for placing concrete overlay based on experimental results. Different surface preparation conditions were investigated while other parameters such as water-to-cement ratio, fine and coarse aggregates, cement and curing conditions were kept constant in order to study the influence of surface preparation on bond strength between the concrete overlay and underlay. The main focus of this research was on studying the effect of changing surface pattern consisting of different groove depth, spacing and the effect of using slurry mix made of overlay ingredients at the bond interface. The results also show that surface preparation without adequate groove pattern provides lower bond strength than the cases in which the groove patterns are implemented.

THE INFLUENCE OF SURFACE PREPARATION ON BOND STRENGTH BETWEEN CONCRETE OVERLAY AND UNDERLAY IN PRESTRESSED SLAB BRIDGES

by

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List of Abbreviations

MDOT	Maryland Department of Transportation
SHA	State Highway Administration
NRMCA	National Ready Mixed Concrete Association
MDF	Medium Density Fiber
gms	Grams
lbs	Pounds
psi	Pounds per Square Inch
in.	Inches
Exp. Condt	Experimental Condition

Chapter 1: Introduction

1.1 Background

The pre-stressed concrete slab bridges are most often subjected to increasing vehicular loads and harsh environmental conditions that can reduce their service life substantially. This creates necessity for repair and rehabilitation which is a very cost sensitive and tedious process that may even lead to temporary closing of a bridge causing delays in access.

Concrete Overlays are useful in extending the service life of bridge decks by providing a durable, improved frictional riding surface and increase the load carrying capacity of the deck. They can also act as sealant on top of the bridge deck and protect the underlying concrete slabs from deicing salt penetration and prevent the corrosion of steel reinforcement. Most of the State Department of Transportation's (DOTs) use concrete overlays to repair or rehabilitate the aging bridge decks. Apart from repair and rehabilitation, the concrete overlays can also be used in new bridge decks to protect them from future damage.

Based on the material used for concrete overlays, they are classified into different types- Portland cement concrete (PCC) overlay, Latex Modified concrete (LMC) overlay, Silica fume concrete (SFC) overlay, Fiber reinforced concrete (FRC) overlay etc.

Latex such as Styrene Butadiene is usually added to provide improved bonding, greater flexural strength and decreased permeability for overlays used on bridge decks. The effective bond between the concrete overlay and the underlying slab or otherwise known as the underlay, has a significant influence on the effective performance of the overlay.

Heavy truck loads on the bridge deck usually lead to the de-lamination of the concrete overlays in cases where the bond strength is inadequate. Thus a crucial component of concrete overlay application is the bond between the overlay and the underlay. The overlay and the deck slab should behave as a monolithic structure for the concrete overlay to perform as intended. Thus the durability of the entire composite system is dependent on the durability of the bond.

Numerous surface preparation methods have been implemented in the past to provide durable bond between the concrete overlay and underlay in concrete bridges. These methods include the use of Portland cement grout, Latex modified cement grout, cement slurry, commercial bonding agents such as epoxy resins, and mechanical crossing devices like shear studs or stirrups at the bond interface. All these methods were used in the past with varied level of success. The overlay bond strength can be tested using shear tests like Double-L test, and tensile tests like the Pull out test, Split prism test etc.

In most overlay bond strength studies, the research on the effect of using different overlay materials or cement slurry with minimal surface roughening has been extensive, but very little research has been carried out on the effect of surface preparation using different groove patterns at the bond interface. Based on comprehensive literature review, the influence of following surface preparation conditions on the bond strength were investigated in this research study:

1. Slurry mix made of overlay ingredients along with typical square grooves;
2. Groove pattern consisting of square grooves of different size and spacing.

1.2 Research Approach

The bond strength between underlay and overlay in prestressed concrete slab bridges has been outlined by the researchers as one of the major causes for early delamination of overlays. In the past, many of the studies on overlay bond strength have paid much attention on the use of slurry mix at the bond interface with very minimum importance given to the surface preparation using groove patterns on bond surface.

Extensive laboratory studies have been carried out to study the influence of slurry mix on the shear and tensile strength of the bond between overlay and underlay in concrete bridges. This research focuses on studying the effect of surface preparation using different groove patterns at the bond surface and its comparison with the use of slurry mix.

The groove pattern at the bond surface consists of square grooves of equal depth and width with a unique center to center spacing between them. This experimental study was conducted using two sample types. The Sample Type 1 was of L shape and the Sample Type 2 was of Prism shape. These samples were prepared in two stages- underlay and the match-cast overlay. As the shape of samples to be prepared were non-standard and the bond surface required groove patterns, all the formwork were made out of lumber.

Grooves were cut to the required depth, width and were fixed to the bond panel, which was replaced with a new panel for all five different test condition studied in this research. Each of the five test conditions was designed, for both sample types, to have unique groove size and spacing with one of the condition using slurry mix. For detailed outline of the test conditions, see Chapter 4.

The underlay samples were prepared using concrete mix with Type-III cement, coarse aggregate, fine aggregate, water and admixture. All the underlay specimens were steam cured using laboratory oven for duration of 18 hours. After the underlay samples were cooled down to the room temperature, and the formwork was striped. The grooves on the underlay sample were cleaned using water jet and compressed air before they were used to prepare the overlay sample. The overlay samples were match-casted using the underlay samples to achieve the overlay bond.

The overlay samples were prepared using concrete mix with Type-I/II cement, coarse aggregate, fine aggregate, water and admixture. The overlay specimens were cured differently than the underlay specimens. They were cured for 28 days in a moist room before testing the shear and tensile bond strength between underlay and overlay. The quality of the concrete mix batches were controlled by preparing and testing cylinders for compressive strength each time a new batch of concrete is mixed throughout the entire research.

The L shape samples were prepared to study the shear strength of the overlay bond. The compression machine available at the NRMCA lab was used to perform this test. One set of L shape overlay samples was tested after curing for 14 days and the remaining three set were tested at 28 days for each of the five test conditions. This was done to check the 90% strength achieved after 14 days of curing.

The tensile bond strength was studied using the Prism samples prepared. The compression machine at NRMCA lab was used with a different load transfer sleeve to suit the testing condition for tensile bond strength. Again one set of prism overlay samples was tested at 14 days of curing to determine the 90% strength achieved by the bond. Other three sets were tested at 28 days.

1.3 Problem Statement

The current practice of the Maryland State Highway Administration (MDOT SHA) and few other state DOTs in the US, is to use the cement slurry as the bonding agent in prestressed concrete slab bridges. Based on the MDOT SHA specifications manual, the guidelines for application of overlays using cement slurry at the bond interface are discussed here.

The reinforcement cage of the overlay slab has to be lifted on and off the underlay surface before placing the overlay. Temporary supports such as diagonal reinforcement bars, or steel angles were to be provided so that the reinforcement cage configuration is not disturbed during the lifting operations. It has to be ensured that the reinforcement was properly laid after leveling up the surface.

After lifting the reinforcement cage was lifted up just prior to the placement of overlay concrete, the deck has to be cleaned thoroughly. The surface directly in contact with the overlay has to be cleaned using methods like abrasive blast. This has to be performed no more than 24 hours prior to overlay placement. It is followed by cleaning of underlay surface with air blast and subsequent water flushing.

The surface has to be wetted for minimum of one hour before laying overlay and it has to be ensured that the concrete deck is not subjected to any additional loads other than that due to construction equipment. Misting operations have to be used to keep the slurry moist as the reinforcement cage for the overlay was carefully placed back in its position.

This has to be followed by placement of concrete mix for the overlay while the slurry is still fluid and has not set. As can be inferred from the above details, the current standard procedure for placement of overlay concrete on new and existing prestressed concrete bridges is very tedious and exhaustive.

It also requires high skilled workers on field for carefully handling the lifting and placing operations. All these factors recommend for studying the effect of using other surface preparation methods to achieve the adequate bond strength between concrete overlay and underlay in prestressed slab bridges.

1.4 Objectives & Scope of This Study

1. Survey current practices used by different state DOTs in the US regarding Concrete overlay specifications and bond strength testing methods;
2. Investigate bond strength between overlay and underlay with different Groove patterns at the bond interface; and
3. Compare and comment on the shear and tensile bond strength results.

1.5 Structure of Thesis

This thesis consists of seven chapters. The first chapter gives introduction and the overall outline of the research. In Chapter 2, a brief review of literature on practices to ensure good bond strength between concrete overlay and underlay is presented.

Chapter 3 discusses the literature on testing of overlay bond strength. Experimental details such as sample preparation, materials used and test methods are precisely given in Chapter 4. Chapter 5 presents the results of L shape samples while the Chapter 6 provides an analysis of results for Prism samples. Finally, Chapter 7 provides summary and conclusions of this study.

Chapter 2: Concrete Overlays

2.1 Introduction

The Concrete Overlays are used to extend the service life of concrete bridge decks by providing a durable and improved frictional riding surface, increasing the load carrying capacity of the deck, and also forming a sealant on top of the deck that protects the underlying concrete slabs or substrate from de-icing salt penetration and reinforcing steel corrosion.

Several materials have been used for concrete overlays, including Portland cement concrete, silica fume concrete; latex modified concrete, fiber reinforced concrete etc. Latex such as styrene-butadiene is often added (15% latex solids by weight of cement) to provide improved bonding, greater flexural strength and decreased permeability for overlays used on bridges (Silfwerbrand et al 2011). Most State DOTs have used at least one type of concrete overlay to maintain or rehabilitate aging pavements and bridge decks (Harrington et al 2007).

A crucial component of concrete overlays is the bond between the underlying slab and the overlay. For the concrete overlay to perform as intended, the overlay and the deck slab on which it is placed should behave as a monolithic structure. The durability of the entire composite system is thus dependent on the durability of the bond.

Several methods have been used to provide good bond strength based on the condition of the underlying concrete. These methods include the use of Portland cement grout, latex modified Portland cement grout, cement slurry, commercial bonding agents such as epoxy resins, and mechanical crossing devices such as shear studs and stirrups.

Each of these methods has been used to varied degree of success. However, the use of bonding agents or slurry mix pose a significant challenge during construction, as their application is very time sensitive an usually requires the contractor removing the reinforcement of the overlay after they have been laid out and cut, thoroughly cleaning the underlay concrete surface, applying the bonding agent or slurry mix, and quickly replacing the reinforcement and casting the slab before the bonding agent or slurry mix sets or dries.

Aside the difficulty and time consuming nature of using bonding agents or slurry mix, there is some evidence in the literature that question their usefulness in concrete overlays when proper surface preparation and placement procedures are followed. Bonding agents have higher water-cement ratios, and more permeable introducing a place of weakness, and can result in lower bond strength. Some researchers believe that bonding agents should be avoided (Harrington et al 2007, Krauss et al 2009, Mccullough and Fowler 1994, Silfwerbrand et al 2011, Trevino et al 2003).

2.2 Overlay Types

Concrete overlays fall in two basic categories- bonded and unbounded concrete overlays. In unbounded concrete overlays, no bond exists between the underlying concrete and the overlay. A separation layer, usually asphalt, is used to prevent bonding between the two layers of concrete. Bonded concrete overlays involve two bonded concrete layers which act as one monolithic structure. In order for bonded concrete overlays to serve their purpose, they have to be able to provide a strong bond to prevent de-lamination or de-bonding.

A complete bond between prestressed concrete slab and the overlay is very critical in order to achieve monolithic action. Bond strength is usually defined as tensile strength perpendicular to the interface plane. However, bond strength in shear may also be considered given its inherent role and intrinsic relationship with tensile behavior (Silfwerbrand 2003, Silfwerbrand et al 2011).

2.3 Bonded Concrete Overlays

The bond mechanism between concrete overlay and underlay depends on the true surface area of contact between the two layers. Traditionally, bonding agents such as Portland cement grout, latex modified Portland cement grout, cement slurry and epoxy resins are sometimes used to improve the bond.

Based on the surface conditions of the underlying concrete, they can improve bond strength. Cement sand slurries or cement latex slurries can be used as bonding agents, but they must be carefully proportioned, mixed and placed. Cement sand slurry is preferable to just cement slurry as it reduces the cement and water content, which could lead to shrinkage cracks.

Grouts also have similar issues with high cement and water demand. Excessive water in the grout will lead to weak bonds. Cement slurries containing non re-emulsifiable latex emulsions can also be used as bonding agent. However, they dry out very quickly and must be covered immediately to prevent surface film formation, which reduces bond strength (Krauss et al 2009).

Common examples of latex include Styrene-Butadiene (SBR) and acrylics. Epoxy latex emulsions have also been used as bonding agents. However, their application is difficult and careful consideration should be given to their formulation as they directly affect their performance. In general primers or bond coats are usually not needed for overlays involving Portland cement concrete, as the paste fraction of the concrete makes a good bonding agent between the overlay (Krauss et al 2009).

Mechanical crossing devices such as nails and stirrups have also been used to strengthen bond. Under less than ideal surface conditions, shear connectors or jumbo nails can be used to improve the bond and load transfer between the two concrete layers. Power driven nails have been studied in Texas for overlays.

Laboratory and full scale tests performed on his system indicated that test sections with the nails performed significantly better than those without nails in terms of early-age drying shrinkage cracking and interface bond strength (Choi 1996, Trevino et al 2003). However, stirrups do not work until bond has broken, because they have to be strained before they can carry any significant load.

There are several issues with using a cementitious bond coat as used currently by Maryland State Highway and other states. They are very tedious and time consuming to construct due to the process of removing the reinforcement, cleaning the underlay surface, placing the slurry, and then quickly placing back the reinforcement and the slab is prepared before the slurry sets, there are other issues too. However, there is some evidence that these bonding agents may not be necessary if proper surface preparation and placements procedures are followed, and they might even be detrimental to the bond integrity by introducing another plane of weakness (Silfwerbrand et al 2011, Trevino et al 2003).

Chapter 3: Surface Preparation and Test Methods

3.1 Introduction

A strong, durable bond between the substrate concrete and the overlay is the most important factor for the reliability of the structures. Many researchers argue that the durable bond in the concrete overlays can be worked out if all operations for concrete removal, surface cleaning, concrete placing, and curing are done carefully with attention to details (Silfwerbrand, Beushausen, Courard, 2011).

The underlay surface should be cleared of dust, unsound concrete and other unwanted particles to develop a good bond. It is widely agreed that a saturated surface dry substrate prior to overlay placement works out best for achieving good bond strengths. It is recommended that the underlay surface is cleaned twice- first time immediately after water-jetting and the other just before laying the overlay concrete. The influence of interface textures were investigated and concluded that smooth surfaces as well as sandblasted surface experience a significant loss of bond strength with time (Talbot et al 1994). However, surfaces which were roughened mechanically and subsequently sandblasted had good bond durability.

Mechanical adhesion between the two layers is a very important factor. Penetration of liquid through the roughness of the underlay surface induces cohesion by interlocking effect.

Workability and proper compaction of the mix of the freshly placed overlay ensures that the cavities and voids on the underlay concrete surface are properly filled. Swedish National Road Administration recommends the use of vibration pokers and vibration platforms to achieve proper compaction. Self-consolidating materials (with high workability) are expected to lead to higher effective contact area and then to higher bond strength.

Properties of the hardened overlay material also influence the bond properties. It is observed in some studies that both- tensile and shear bond strength are proportional to the early age concrete strength. Excessively impermeable overlays result in stresses at the interface when moisture from the underlay cannot migrate through the overlay. The bond strength is also a function of the underlay surface temperature. Cold substrate (at 4'C) results in a lower initial bond strength but higher long-term bond strength in comparison to substrates at higher temperatures (21'C or 38'C).

Use of grouting material such as cement slurry used in the current practice by the Maryland State Highway Administration is also a good practice to ensure good bonding at the interface but very tedious. They may improve bond strength for certain materials and are recommended for stiff repair mortars that cannot properly fill open pores and cavities on the underlay surface.

Once the overlay concrete is laid out on the underlay surface, it should be subjected to a minimum of five days of water curing for proper strength development. During the curing regime, exposure to direct sunlight was found to have a detrimental effect on the shear bond strength. Once the overlay concrete is placed, continuous and limited vibrations due to moving traffic may increase both the overlay strength and the bond strength.

However, heavy vibrations starting a few hours after overlay placement should be avoided. The best way of preventing heavy vibrations is to maintain a smooth riding surface and a smooth transition at the expansion joints of the bridge (Manning 1981).

3.2 Methods for Surface Preparation

A Several factors affect the bond strength, including the material properties of the fresh and hardened concrete, environmental conditions, surface preparation and properties such as cleanliness and roughness, bonding agents and mechanical crossing devices. Of all factors that influence bond strength, the surface preparation and cleaning of the underlay concrete surface is the most important.

Common surface preparation methods used in new or rehabilitation works of bridge decks include mechanical roughing and blast methods using abrasive, high pressure water, or a mixture (Bissonnette et al 2012).

In the following sections, different surface preparation methods that affect the bond characteristics are discussed.

3.2.1 Slurry Coat

The slurry specifications according to the Maryland State Highway Administration manual 440.02.05 were considered in this research. To prepare the slurry, equal parts by weight of Portland cement and sand mixed with sufficient water.

It is to be ensured that the consistency of the slurry mix allows for application of the mix with a stiff brush or a broom in a thin, even coating that will not run or puddle. The state of Indiana spreads slurry coat of the same material as the overlay on the cast in place decks of the bridges before applying the overlay on top of it.

3.2.2 Bonding Agents

The Bonding agents are usually employed to improve the bond characteristics of the interface between the underlay and overlay surfaces. This helps to improve the cohesion and integrity of the bon between the two surfaces. If bonding between the substrate and the overlay is not durable, water, de-icing salts may seep through the overlay to the underlay surface due to poor adhesion and affect the structural strength of the bridge deck.

It is imperative that the underlay surface is treated properly, cleaned of any dust and/ or unsound concrete particles before application of suitable bonding agent (Silfwerbrand et al 2011). Based on the studies, it is noted that the use of bonding agents cannot compensate for poor surface treatment. Moreover, it requires very careful attention and can instead ac as bond breakers if not used properly.

The grout has a higher water-cement ratio that reduces the strength and induces risk of a cohesive failure within the bonding agent itself. It is advised to use them for very stiff mortars so that they can properly fill the pores/ grooves on the underlay surface for better interlocking and bond strength.

Methods like scarifying and acid etching are used to create grooves to prepare the surface for receiving the overlay.

Of the different commercial bonding agent products available in the market, a few products that are widely used to provide an effective bond between the underlay and overlay are Dural Prep AC, Flexi Bond 540, Sika Aramtec 110, Enecon Eneclad superbond.

Any bonding agent ultimately acts a product that can join the overlay and the precast element so that there is no requirement for mechanical fastening. But it is to be noted that the improper application of bonding agent leads to plane of weakness at the bond interface.

3.2.3 Shear Studs

The case where shear studs are used is the case where the mechanical bond between both interfaces developed b employing use of No.3 bars as shear studs that protrude 2” into the overlay. Missouri Department of Transportation uses a mechanical bond (reinforcement) between the overlay and the precast element. The reinforcement should be sufficiently anchored in layers of overlay and the underlay concrete (Silfwerbrand, Beushausen, Courard 2011). At the same time using shear studs for providing a mechanical bond can create other handling issues.

3.2.4 Groove Pattern

In the current practice by the MDOT SHA, the underlay surface is raked before the slurry is laid on its surface. This allows the underlay surface to develop certain roughness that aids in better interlocking and bond strength at the interface. Many researchers argue that up to a certain threshold surface roughness, the bond strength increases and then levels out (Silfwerbrand, Beushausen, Courard 2011).

This threshold surface roughness is provided using methods like sand-blasting, hydro demolition etc, which are also useful in clearing the laitance from the top of the underlay surface. The roughening of the underlay surface can also be done by providing square grooves at certain spacing between adjacent grooves on the underlay surface and cleaning thoroughly with water before the overlay is cast.

The size and spacing of the square grooves are varied and their effect is studied in this research. The roughness of underlay surface provided by the grooves is very important to ensure strong bond condition at the interface.

3.3 Methods for Bond Strength Testing

Several test methods and set-ups have been developed for testing interface bond strength of concrete overlays. At the interface between underlying concrete and overlay, both shear and tensile stresses are present (Delatte et al 2000). The results and interpretation of these tests vary substantially and depends on specimen size, test set-up, loading rate and whether the test is performed in-situ or in the laboratory. However, these tests methods can be broadly categorized into direct shear, shear-compression, and tension tests.

In direct tension tests, the specimen is pulled apart by loads applied perpendicular to the bonded interface. The pull-off test is most popular test in this category and is easy to set up. It can be performed in-situ and in the lab. A core is drilled through both overlay and underlying concrete. In the lab, the pull-off test gives reliable results when the test is performed with the lowest possible eccentricity (Silfwerbrand et al. 2011). This test is outlined in ASTM C1583.

Shear test methods involve applying shear forces parallel to the bond interface. However, if the test specimen consists of two parts as is the case with shear block tests, a bending moment is developed as soon as the load is applied.

Delatte et al. (2000) reported issues with eccentricity using shear block tests developed by Choi (1996), which resulted in lower bond values. To solve this problem, a test method consisting of three parts is used. However, these test methods also have the disadvantage of having two interfaces instead of one, which hardly exists in reality (Silfwerbrand et al. 2011).

Ray et al. (2005) developed a test based on ASTM D905 (shear bond test for adhesives) that evaluates the interface performance of bi-layer composites through direct shear without the load being applied directly at the interface. These tests achieved consistent results for bond strength for commonly used overlay materials; however there were issues with rotation of specimen at high bond strengths. The guillotine test method solves the problem of moments and two interfaces, and has been used extensively (with some success) for measuring concrete-to-concrete bond despite the difficulty in aligning the bond plane precisely to eliminate bending (Delatte et al 2000, Wade et al 1995).

Due to wide variability of test set ups in the literature, a comprehensive study of different types of bond strength tests is performed to select test methods that are most suitable for the stated objectives of this research. The test methods studied are discussed in detail in the following sections.

3.3.1 Split Prism Test

The Split Prism test is a standard test for quantifying the tensile strength of prismatic concrete specimens. It is also known as splitting tensile test. For the experimental setup, two halves of split prism – underlay cast with Type 3 cement and subjected to steam curing regime and the overlay match-cast with Type 1 cement subjected to normal moist-curing for 28 days are used. The typical size of each half in the specimen is 6” x 6” x 3”. The setup for the test is shown below.

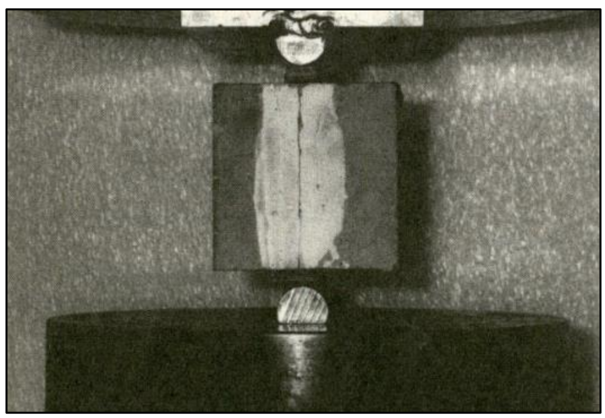

Figure 3.1 Split Prism Test

3.3.2 Slant Shear Test

The slant shear test measures the bond strength under a combination of shear and compression. This test method is described in detail in ASTM C 882/C 882M-05. It is used to determine the bond strength of bonding systems for use with concrete. Epoxy system is used to bond together two identical 3 x 6 cylindrical sections.

The bonding area is at an angle of 30° with the vertical line. Once the specimen is cured, the test is performed to determine the compressive strength of the composite cylinder. The specimens are tested at the standard temperature of 73 + 2 °F in compression. The total load carried by the specimen at failure is recorded and it is divided by the bonding area to get the bond strength of the composite cylindrical specimen. If any voids are found in the bond on inspection after test, reduce the area of the bonded area used in preceding calculations so as to account for these voids. In this reduction, neglect any voids that are not larger than ⅛ inch.

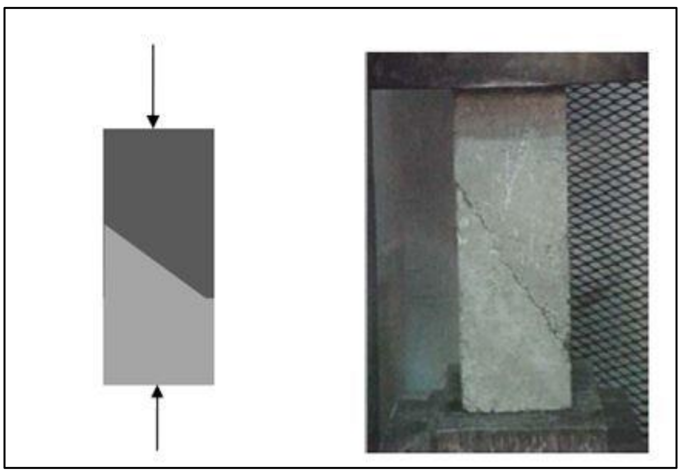

Figure 3.2 Slant Shear Test

Several researchers have indicated shortcomings with this test (Silfwerbrand et al. 2011) due to unrealistic loading conditions, while others have highlighted its sensitivity to surface roughness of the underlying concrete (Júlio et al. 2004) – an essential component of bond strength.

In the slant shear tests (Júlio et al. 2004), significant coefficient of variations were observed between different surface roughness conditions such as wire-brushing, partially chipped, partially chipped & pre-wetted and sand-blasting that are employed in the test.

3.3.3 Push off Test

The push-off test also known as the L-shaped test is a shear test normally used to assess bond strength when there is steel reinforcement such as stirrups or nails crossing the bond interface. Choi et al (1999) also describe an in-situ (though performed at the lab) push-off test to evaluate shear transfer across bonded concrete overlay interfaces reinforced with power driven nails. In their proposed method, two PVC pipes are embedded into the cast overlay concrete with a high-strength threaded steel bar inserted through each pipe. One end of the threaded bar is connected to a front loading head, while the other end is tightened against the back of a mild steel plate.

Two hydraulic cylinders are used to apply loads at the back side of the overlay through the steel back plate along the centerline of the interface to apply shear to the interface. In their set-up, there was a small eccentricity (20mm) because the centerline of the steel bars was not right at the interface, but they considered this moment negligible. This test is very sensitive to the surface roughness of the interface.

In the test setup, heavily shot-blasted surface experienced no significant relative slip at the interface until the peak load of 81 kN; the displacement was 0.3 mm. On the contrary, in case of lightly shot-blasted surface, the overlay started slipping when the shear load reached half of the peak value of 70 kN. Displacement of 1.1 mm was recorded at the peak load in this case. For test cases with no nails in the base concrete, the total slip at the interface was observed to exceed 10 mm.

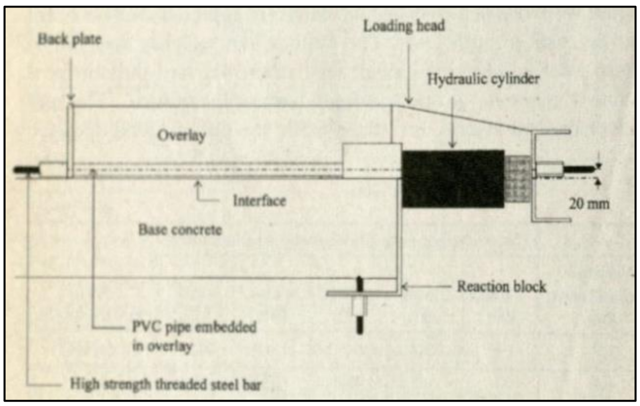

Figure 3.3 Push off Test

There was no significant difference in peak shear loads for surfaces subjected to different surface treatments. It was observed that the displacements at peak loads were larger for overlay specimens with nails. This is attributed to the redistribution of stresses across the interface surface after the adhesion was lost. Many overlay specimens with nails prematurely failed in low-strengths concrete (base concrete or overlay) before the interface failure. These observations indicate that the interface shear strength of overlay specimens with nails is lower than those without nails.

Insufficient interface preparation leads to a reduced interface shear strength in these tests. Interface strength of cracked specimens was lower than that of un-cracked specimens.

3.3.4 Pull off Test

The pull-off test is outlined in ASTM C1583-04. It is a direct tension test; the composite specimen is pulled apart by loads perpendicular to the bonded interface. In this test, a shallow core is drilled through the substrate perpendicular to the surface and a steel disk is attached to the top face of the specimen. The disk is subjected to a tensile load until the specimen fails when the corresponding load is noted to compute the tensile strength of the interface. In this method, the load at the failure of the specimen is governed by the region where the failure occurs along the path of the load.

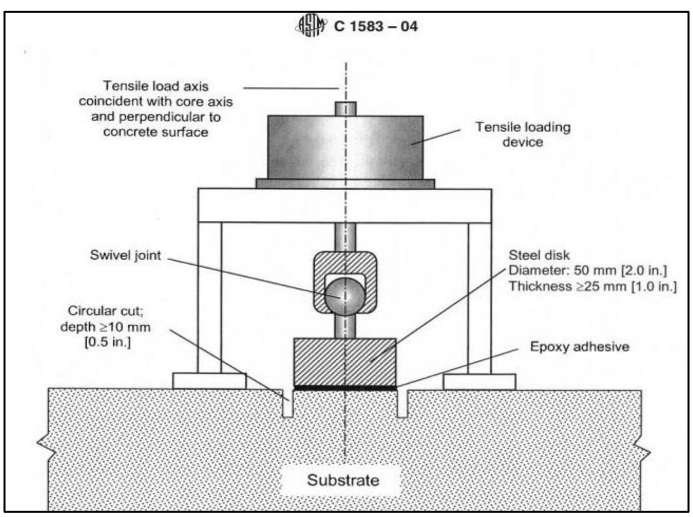

Figure 3.4 Pull off Test

The specimen surface is to be free of any standing water and clean of any debris. Epoxy adhesive is used to attach the steel plate to the top face of the specimen. Tensile load is applied at the standard constant rate concentric to the plate & the specimen so as to avoid any eccentricity of load. If the failure occurs at the bond interface between the substrate and the overlay, the load at failure gives the tensile bond strength of the specimen. This load is divided by the bond surface area to compute the bond tensile strength.

3.3.5 Double L Test

In research conducted by Strategic Highway Research Program (SHRP), an experiment is done to determine the interfacial bond strength of two concrete layers using a Double L Test. In this method, two L shaped concrete specimens – underlay cast using Type 3 cement and subjected to steam curing process to simulate action of the pre-stressed underlay slab and the second one is the equivalent of the overlay slab match cast using Type 1 cement and conventional 28 days curing process.

Both specimens are provided nominal & identical steel reinforcement to ensure that the specimen fails due to shear failure in the interface plane. In this setup, it is very critical that the line load from the test machine coincides with the interface plane to ensure zero or minimal eccentricity with respect to it so that the failure plane is subjected to a direct shear condition.

The bonded faces of the reinforced specimens are as shown in the figure below. This method allows us to predict shear strength of the concrete overlay bond with the underlay.

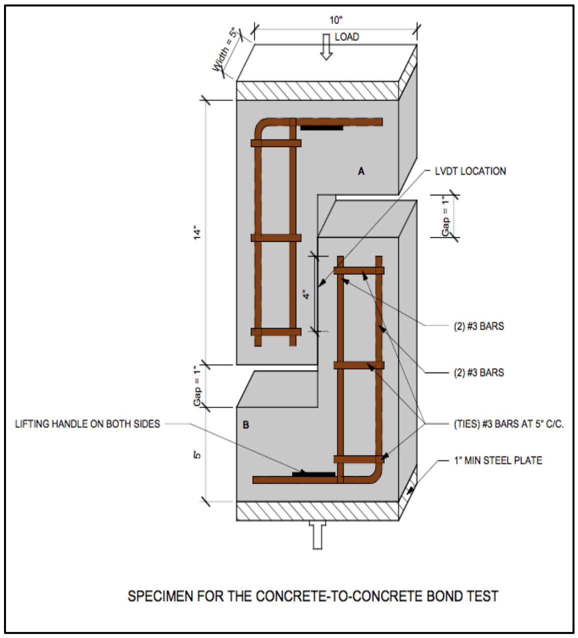

Figure 3.5 Double L Test

3.4 Survey Responses from State DOTs

A survey is conducted through University of Maryland for the Maryland State Highway Administration, Office of Structures, for a research related to developing best practices for placing reinforced concrete overlays on prestressed slab bridges. The purpose of this survey is to identify the current practices used by other State Department of Transportation's (DOTs) in order to ensure good adhesion between the concrete overlay and the prestressed concrete planks (slabs);

Also to identify any test methods that may have been adopted to test the bond strength of concrete overlays. Of the states that responded to the survey, the states that do not use Overlay in bridge decks and/or prestressed planks in bridges are Alaska, Florida, Louisiana, Mississippi, Oklahoma and South Dakota. New Jersey DOT responded that it does not have any standards and specifications for prestressed slab bridges and neither do they use any Mechanical methods like shear studs or reinforcement to ensure bond between overlay and the prestressed concrete planks.

Roughening the surface profile on top of prestressed planks is a common practice observed from the responses received from various state DOTs. The states that use this kind of surface roughening are Delaware, Indiana, New Hampshire, Tennessee, Texas, Vermont and West Virginia. The roughening is usually as per AASHTO specifications as mentioned by New Hampshire. Indiana uses Hydro demolition techniques to prepare the prestressed plank surface before overlay is placed. In some cases like West Virginia, the DOTs instruct the box beam fabricators to roughen the surface of the box beam.

Chapter 4: Sample Preparation, Materials and Test Methods

4.1 Introduction

Two types of specimen were prepared in this research study, 6” prisms and Double-L shape sample. The 6” prisms were used for tensile strength testing of the overlay bond and the Double-L shape sample for shear strength testing of the overlay bond. The samples were prepared in accordance with the MDOT SHA mix design requirement and the actual conditions implemented by the precast slab manufacturer. Both the samples were provided with grooves in fresh concrete using adequate formwork, instead of raking as suggested by the precast slab manufacturer.

4.2 Materials

4.2.1 Formwork

Formworks were made using 3/4“lumber with provisions for grooves on the bond surface of the underlay. The L-shape underlay sample and the prism underlay sample were prepared using different formwork assemblies. The variation in groove pattern or the surface preparation was achieved using bond panels of different groove configurations as mentioned earlier. In the case of L-shape sample, the size of bond panel was 8” x 5” which is effectively the overlap with the overlay material during match-cast.

Similarly in the case of prism sample, the size of bond panel was 6” x 6”. In both the cases, the bond surface was kept vertical for preparing underlay samples so as to enable adequate flow of aggregates into the groove patterns.

Figure 4.1 Formwork- L shape Underlay samples

Figure 4.2 Formwork for Prism Underlay samples

Once the underlay samples were prepared, the overlay samples were match-casted using a new formwork separately for both L-shape sample and the prism sample. The prism overlay sample was prepared by placing the prism underlay sample in such a way that the bond surface remained horizontal. In the same way, the overlay sample of L-shape is prepared by placing the L-shape underlay sample in the formwork such that the bond surface remains horizontal.

Figure 4.3 Formwork for Prism Overlay samples

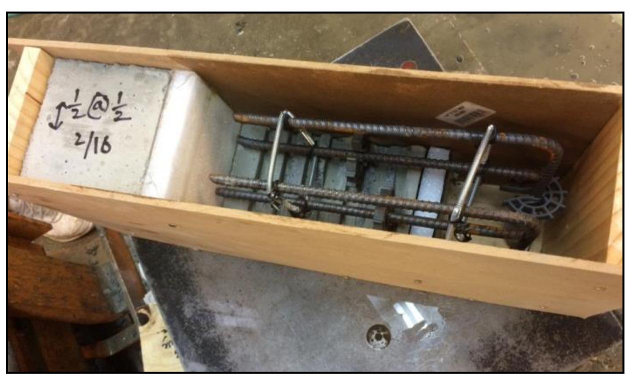

Figure 4.4 Formwork for L Shape Overlay samples

4.2.2 Cement

Portland cement of two different types was used throughout the entire research. Type-III early strength cement was used in preparing underlay as the curing was accelerated using a steam oven. The Type-III was used because the overlays are required to be match-casted immediately after the underlays were steam cured using oven.

Type-I cement was used in preparing overlays, which were cured for 28 days using normal moist conditions. It was ensured that all the cement used in the entire research was produced from the same batch by the supplier.

Figure 4.5 Cement bags of Type-III & Type I/II

4.2.3 Coarse Aggregates

The coarse aggregate used in the entire research was No.8 size crushed stone, which was required by the Maryland State Highway Administration (MDOT SHA) for concrete overlay applications. The crushed stone was obtained from the nearby Quarry in Maryland and was readily available for use at the NRMCA lab.

Figure 4.6 Coarse aggregates

The crushed stone available at the NRMCA lab was tested before usage, conforming to the No 8 Stone sieve analysis results. A representative sample weighing 5000 grams was taken and the sieves are vibrated for duration of 10 minutes using standard apparatus at the NRMCA lab. The results are shown in Table 4.1.

Table 4.1 Sieve analysis of coarse aggregates

Sieve Size	1"	3/4"	1/2"	3/8"	No. 4	No. 8
Weight retained (grams)	-	-	45.6	953.2	3407	466.4
Weight of aggregate finer than (%)	100	100	99.09	80.02	11.88	2.56

The moisture content of the coarse aggregate was measured to be 0.45 %, using the dry weight and the moist weight of the coarse aggregate. A representative sample of 5000 grams coarse aggregate was taken and placed in oven overnight and the dry weight was recorded next day. The moisture content of the coarse aggregate was calculated before each batch of concrete was mixed and was used as an input for the mix design.

Table 4.2 Moisture content of coarse aggregate

Weight of sample (gms)	5000
Dry weight (gms)	4977.5
Moisture content (%)	0.452

Moisture content (%) = 100 x (Weight of sample - Dry weight)/ Dry weight

4.2.4 Fine Aggregates

Manufactured sand conforming to the Maryland State Highway Administration requirement was used throughout the research. The manufactured sand was obtained from the nearby Quarry, Maryland.

Figure 4.7 Fine aggregates

The moisture content of the fine aggregate was measured to be 3.3%. A representative sample of 5000 grams fine aggregate was taken and placed in oven overnight and the dry weight was recorded next day. The moisture content of fine aggregate was calculated before each batch of concrete was mixed and was used as an input for the mix design.

Table 4.3 Moisture content of fine aggregate

Weight of sample (gms)	5000
Dry weight (gms)	4840.7
Moisture content (%)	3.29

Moisture content (%) = 100 x (Weight of sample - Dry weight)/ Dry weight

4.2.5 Admixtures

Admixtures of two types were used in throughout the entire research. The first admixture used was SIKA AEA 14 which is an air entraining admixture to control the amount of air entrained in the concrete mix. The air entrainment was kept as 2%, as per the requirement of the Maryland State Highway Administration for the concrete overlay applications.

Figure 4.8 Admixtures used in the concrete mix

The SIKA AEA 14 was measured and added to the required mix water quantity each time before the mix was started. The other admixture that was used is SIKA Viscocrete 2100, which is high performance water enhancing admixture. This admixture was used for increasing the workability of concrete mix to ease the pouring into formwork, mainly at the time of mixing underlay concrete as the Type-III cement causes the mix to set very early. The SIKA Viscocrete 2100 is added to the fresh concrete each time before the final round of mixing.

4.2.6 Mix Design

The batch size of the concrete mixes was designed taking into consideration the mixer capacity and the oven size in case of underlay samples. To make it consistent throughout the entire research, the L-shape samples and the prism samples were prepared separately.

Figure 4.9 Concrete Mixer

The first mix was for preparing L-shape sample along with the cylinders for checking the mix design compressive strength. In the second mix, the prism samples are prepared along with the cylinders. The mix design for overlay sample was done in a similar way, except that the numbers of cylinders prepared are different from the underlay mix.

The overlay mix was prepared using Type-I cement and the amount of admixture SIKA Viscocrete 2100 was different as the mix is more workable compared to the underlay mix.

Table 4.4 Mixing Proportions for Each Batch of Concrete Mix

	L-shape Overlay Sample					Prism Overlay Sample				
Mix	1	2	3	4	5	1	2	3	4	5
Cement (lbs)	59.3	59.3	59.3	59.3	59.3	23.7	23.7	23.7	23.7	23.7
Coarse Aggregate (lbs)	98	98	98	98	98	36.8	36.8	36.8	36.8	36.8
Fine Aggregate (lbs)	58.5	58.5	58.5	58.5	58.5	23.4	23.4	23.4	23.4	23.4
Water (ml)	9772	9772	9772	9772	9772	3900	3900	3900	3900	3900
SIKA AEA 14 (ml)	42.07	42.07	42.07	42.07	42.07	15.8	15.8	15.8	15.8	15.8
SIKA Viscocrete 2100 (ml)	-	-	-	-	-	-	-	-	-	-

	L-shape Underlay Sample					Prism Underlay Sample				
Mix	1	2	3	4	5	1	2	3	4	5
Cement (lbs)	66.2	66.2	66.2	66.2	66.2	26.5	26.5	26.5	26.5	26.5
Coarse Aggregate (lbs)	98.1	98.1	98.1	98.1	98.1	36.8	36.8	36.8	36.8	36.8
Fine Aggregate (lbs)	52.5	52.5	52.5	52.5	52.5	21	21	21	21	21
Water (ml)	9822	9822	9822	9822	9822	3919	3919	3919	3919	3919
SIKA AEA 14 (ml)	47	47	47	47	47	18	18	18	18	18
SIKA Viscocrete 2100 (ml)	64	64	64	64	64	25	25	25	25	25

In every concrete mix, the cement, coarse & fine aggregates, water & admixtures were measured using weighing machine and stored in plastic buckets with letter codes for identification. Measured aggregates are stored as shown below.

Figure 4.10 Batched quantities for a Concrete Mix

Slump was measured for each batch of underlay and overlay concrete mix and was observed to be within the recommended range by the MDOT SHA. The results from the slump cone test are shown in the Table 4.5.

Table 4.5 Slump for Each Batch of Concrete Mix

	L-shape Sample					Prism Sample				
Mix	1	2	3	4	5	1	2	3	4	5
Underlay Slump	6.5	8	7.5	7	7.5	5.5	6.5	6	5.5	6.5
Overlay Slump	4	3.5	3.5	4	2	3	3.5	3.5	4	4

Figure 4.11 Slump cone test

4.3 Sample Preparation

4.3.1 Underlay Samples

The underlay samples were prepared in the NRMCA concrete laboratory as per the standard practice for making specimen in the laboratory. The curing of underlay specimen was done using a steam oven so as to accelerate the curing process.

The non standard shape and the requirement of grooves on the bond surface between underlay and overlay, made it necessary to use custom made formwork using lumber.

Figure 4.12 Non Standard shape of Underlay Specimen

The 3” x 6” x 6“prism underlay specimens and the L-shape underlay specimens were prepared along with the 4” x 8” cylinders. The prism and L-shape underlay specimens were later used to prepare the overlay specimens by the process of match-casting to achieve overlay bond.

4” x 8” cylinders were used to measure the mix design strength each time a new mix is prepared. The L-shape underlay samples are reinforced using No.4 bars bent in the shape of L and 1/4” stirrups to hold them together.

This was done to avoid any failure in the concrete before bond failure. The prism samples were not reinforced as their shape remains standard. The reinforcement cage used in L-shape samples is shown below.

Figure 4.13 Reinforcement for L-shape specimen

The underlay concrete was mixed using Type-III cement, No 8 stone, manufactured sand and water as per the mix design. Admixtures were used to control the air entrainment and the workability of the concrete mix. The underlay concrete batches were mixed in an electronically driven mixer. The exposed parts of the specimens were covered with aluminum foil to prevent any drying.

Table 4.6 Total number of Underlay samples prepared

	Groove		Underlay samples prepared		
Type	Depth	Spacing	L-shape	Prism	Cylinders
1	0.375	1	4	4	3
2	0.5	1	4	4	3
3	0.25	1	4	4	3
4	0.25	0.75	4	4	3
5*	0.25	1	4	4	3
		Total	20	20	15

*Slurry at bond surface

Figure 4.14 L shape Underlay sample

Figure 4.15 Prism Underlay sample

4.3.2 Overlay Samples

The overlay samples were prepared in the NRMCA laboratory as per the standard practice for preparing specimen. The main difference between the underlay and overlay samples is the use of Type-I cement instead of the Type-III cement used in the case of underlay sample preparation. Also the overlay samples are cured normally in a moist room.

The sizes of overlay sample remain same as that of the underlay i.e. 3” x 6” x 6” prism and the L-shape overlay specimen. These are match-cast using the already prepared underlay sample to get a bond interface with different groove patterns.

Figure 4.16 Overlay sample preparation

The L-shape overlay samples are reinforced using No.4 bars bent in the shape of L and 1/4” stirrups to hold them together. This was done to avoid any failure in the concrete before bond failure. The prism samples were not reinforced as their shape remains standard.

Figure 4.17 Reinforcement for L shape Overlay

The overlay concrete was mixed using Type-I cement, No 8 stone, manufactured sand and water as per the mix design. Admixtures were used to control the air entrainment and the workability of the concrete mix. The overlay concrete batches were mixed in an electronically driven mixer.

Table 4.7 Total number of Overlay samples prepared

	Groove		Overlay samples prepared		
Type	Depth	Spacing	L-shape	Prism	Cylinders
1	0.375	1	4	4	4
2	0.5	1	4	4	4
3	0.25	1	4	4	4
4	0.25	0.75	4	4	4
5*	0.25	1	4	4	4
		Total	20	20	20

*Slurry at bond surface

Figure 4.18 L shape Overlay sample after Match-casting

Figure 4.19 Prism Overlay sample after Match-casting

4.3.3 Curing Conditions

The conditions implemented for curing of the underlay and overlays were very important in achieving the desired strength of concrete mix and the overlay bond.

Different curing conditions were implemented based on the type of cement used in preparing the concrete mix. In the case of underlay samples, the specimens were cured using a laboratory oven. This was done as the cement used for underlay samples is Type-III which required attaining early strength.

The underlay samples were placed along with water bowls in the oven and the temperature was raised from 30’C to 60’ C for 1.5 hours and then maintained at 60’C for 15 hours. The specimens were kept overnight in the oven and then the temperature was brought down to 30’C for 1.5 hours. Aluminum foil was used to cover the exposed surfaces of the underlay specimen to prevent drying and shrinkage. Before the underlay samples were placed in the oven for steam curing, they were kept at room temperature for a preset time of 4 hours.

Figure 4.20 Underlay Placed in Laboratory Oven for curing

The entire duration of the steam curing using oven for the underlay samples is 18 hours which includes the time for raising the temperature, constant temperature time and the time for bringing down to the room temperature. After taking out from the oven, the formwork is removed without damaging the grooves on the bond surface.

Figure 4.21 Removing Bond Panel

The overlay samples on the other hand were placed in the moist room and the formwork was removed after 3 days. After the formwork was removed, the overlay samples were again placed back in the moist room and left for a total of 28 days for curing before they were tested for bond strength. All specimens were marked with different letter codes to reflect their date of preparation, groove type & direction.

Figure 4.22 Prism Overlay Samples placed in moist room for curing

Figure 4.23 L shape Overlay Samples placed in moist room for curing

4.3.4 Field Conditions

The Maryland State Highway Administration (MDOT SHA) procures the prestressed slabs from the Northeast Precast Plant in Cressona, PA. The grooves on the bond surface are made using raking tools after the slab is prepared. The curing of underlay is done using steam curing procedure. Similar procedures were implemented while preparing the underlay specimen in the entire research.

The only difference from the actual field condition to the samples produced in this research was the method used for producing grooves on the bond surface. The grooves were made in fresh concrete using adequate formwork panels with imprinted patterns, which produced the same or superior groove quality as produced using raking techniques implemented by the precast plant.

Figure 4.24 Underlay Groove bond panel

The conditions implemented for overlay sample preparation were same as the ones recommended by the MDOT SHA using standard match-casting and curing techniques.

4.4 Test Procedures

4.4.1 Compressive Strength

The cylinders of size 4” x 8” were prepared using standard moulds to test the compressive strength of the concrete mix for each batch. A total of 3 cylinders were prepared for each batch of underlay concrete mix. These cylinders were covered with aluminum foil and steam cured for 18 hours along with the other underlay samples.

Figure 4.25 Underlay cylinders after Steam curing

The underlay cylinders were tested after cooling before the overlay samples were prepared to check the compressive strength of underlay concrete mix. In case of overlay concrete mix, a total of 4 cylinders of 4” x 8” size were prepared.

Curing was done for 28 days in the moist room along with the other overlay samples, before they were tested for compressive strength.

Figure 4.26 Overlay cylinders placed in moist room for curing

Both the underlay and overlay cylinders were tested using standard compressive testing apparatus at a load rate of 30 lbs/s. The cylinders were placed within the metal caps and wrapped with a sleeve to avoid abrupt cracking. The load was increased at the standard load rate until the failure is observed

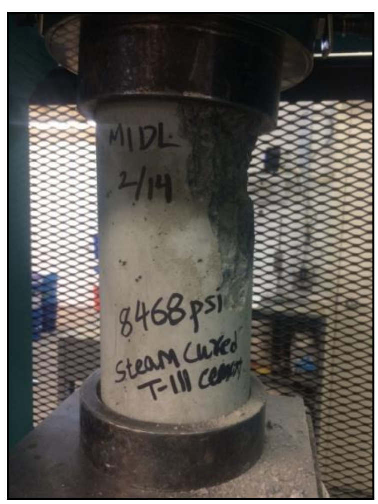

Figure 4.27 Compressive Test of Cylinder

4.4.2 Shear Bond Strength

The shear strength at the bond interface between underlay and overlay was evaluated using the Double L shear test. The load was applied as compression in line with the bond surface to ensure the load to act as pure shear. The match-casted L shape overlays were tested at different stages of curing to determine the shear bond strength.

The test was performed using the standard compression testing machine at the NRMCA lab with a constant loading rate of 25-30 lbs/s. The size of the bond interface was 8” (depth) x 5”(width). The load at failure was measured over the bond interface area (40 in2) to obtain the bond strength in each of the five (5) types of Double L sample.

Figure 4.28 Shear Bond Test of L shape sample

4.4.3 Tensile Bond Strength

The tensile strength at the bond interface between underlay and overlay was evaluated using the Split Prism Tensile test. The load was applied as compression in line with the bond surface until splitting is observed at the bond surface. The match-casted prism overlays were tested at different stages of curing to determine the tensile bond strength.

The test was performed using the standard compression testing machine at the NRMCA lab with a constant loading rate of 25-30 lbs/s. The size of the bond interface was 6” (depth) x 6”(width). The load at failure was measured over the bond interface area (36 in2) to obtain the bond strength in each of the five (5) types of Prism sample.

Figure 4.29 Tensile Bond Test of Prism sample

Chapter 5: Double L Samples

5.1 Introduction

The potential for deterioration of concrete overlays on the prestressed slab bridges due to weak bond between the overlay and the underlay concrete has been widely recognized in the industry. In this research, five (5) types of bond surface conditions were tested for shear bond strength using L shape samples. The L shape underlay samples were prepared with Type-III concrete mix and steam cured for 18 hours in a laboratory oven. Along with the L shape underlay samples, 4” x 8” cylinders were prepared to check the compressive strength of each batch of concrete mix.

Table 5.1 Double -L Underlay samples prepared

Type	Groove		Underlay samples prepared	
	Depth	Spacing	L-shape	Cylinders
1	0.375	1	4	3
2	0.5	1	4	3
3	0.25	1	4	3
4	0.25	0.75	4	3
5*	0.25	1	4	3
		Total	20	15

*Slurry at bond surface

The cylinders were tested for compressive strength before the L shape overlay samples were prepared. The overlay sample was prepared for each type of underlay sample by match-cast technique to achieve the bond at the interface of underlay and overlay. The Double L samples resulted from the match-cast of overlay with the underlay were cured in moist room for 28 days. Again 4” x 8” cylinders were prepared along with the L shape overlay samples to check the compressive strength of each batch of overlay concrete mix.

Table 5.2 Double-L Overlay samples prepared

	Groove		Overlay samples prepared	
Type	Depth	Spacing	L-shape	Cylinders
1	0.375	1	4	4
2	0.5	1	4	4
3	0.25	1	4	4
4	0.25	0.75	4	4
5*	0.25	1	4	4
		Total	20	20

*Slurry at bond surface

Early measurements of shear strength of the bond were made after curing the Double L sample for 14 days. A total of four (4) Double L samples were prepared for each type of bond condition. One of the Double L sample in each type of bond condition was tested after 14 days of curing and the remaining three (3) were tested for the shear bond strength after 28 days of curing in the moist room.

5.2 Influence of Steam Curing

As indicated earlier, throughout this entire research, the concrete mix using ASTM C150 Type-III cement was used for the underlay samples. The underlay sample was subjected to a steam curing regime for quick attainment of the design compressive strength. The Type-III cement has a higher Blaine value; a value that represents the fineness of the cement particles. The increased fineness of the particles allows them to hydrate at a much faster rate and attain up to 70% of the design 28 days strength in less than 24 hours (Lee, C., Lee, S. & Nguyen, N. 2016). The use of this cement type is observed to be a very standard practice in the precast prestressed concrete industry.

Moreover, the use of Type-III cement results in energy conservation during the steam curing process in that it allows same strength development for a reduced temperature and process duration. In the literature, it was found that a maximum temperature between 60ºC and 70ºC and a delay period of three to five hours are optimal values for the steam curing regime. Also, it is proposed that the rate of temperature increase of the specimen should be between 22ºC/hour and 33ºC/hour for optimal strength results without experiencing any excessive volume changes in the specimens (Ramezanianpour, Khazali & Vosoughi 2013). As for the steam curing regime in this research, the freshly prepared specimen was initially left outside for a preset time of 3 hours.

After placing the underlay samples inside the oven, its temperature was increased to 60ºC uniformly at a rate of 20ºC/hour from the ambient temperature. The oven temperature was maintained at 60ºC for duration of 15 hours and was subsequently cooled uniformly to the ambient temperature at 20ºC/hour.

Nine (9) Cylinders of size 4” x 8” were prepared using Type-III concrete mix from the same batch to study the changes in compressive strength of cylinders by keeping all factors similar except the preset time for steam curing. The preset time or the time for which the samples are initially kept at normal room temperature to gain initial strength was considered as Zero (0) for the first set. The 4” x 8” cylinder samples were prepared and immediately placed in the oven for steam curing following the regime explained earlier. The second set of 4” x 8” cylinder samples were prepared and placed at normal room temperature for 1.5 hours before placing in the oven to start the steam curing regime.

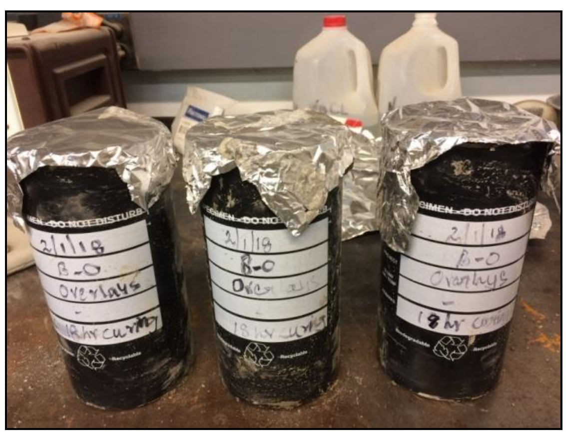

Figure 5.1 Steam curing of 4” x 8” cylinder samples

In the third set the 4" x 8" cylinders were prepared and placed in the oven for steam curing after three (3) hours of preset time. The three set of 4" x 8" cylinders were steam cured with an 18 hour cycle time and allowed to cool to the normal room temperature. The cylinders were then tested for compressive strength attained by the mix using the compressive strength testing machine at NRMCA. The results from the compressive strength test are listed below and are plotted in the Figure 5.2.

Table 5.3 Influence of Preset Time on compressive strength of steam cured underlay cylinders

Cylinder Compressive strength (psi)	Preset time (hrs)		
	0	1.5	3
c1	3480	4326	6500.1
c2	3326.8	4112	6080.5
c3	3841	4203	6237
Average	3549.27	4213.67	6272.53

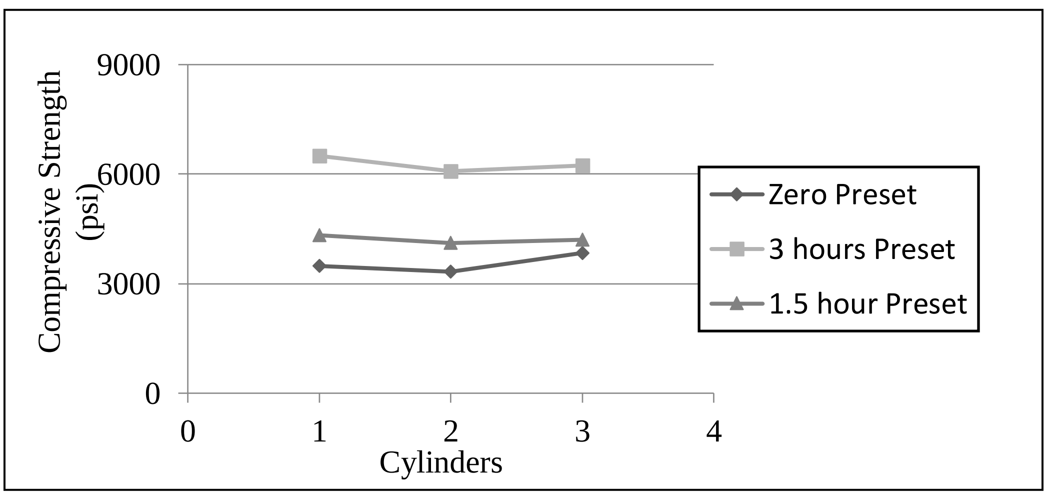

Figure 5.2 Influence of Preset Time on compressive strength of steam cured underlay cylinders of size 4" x 8"

The curves show that the 4” x 8” cylinders steam cured with a preset time of three (3) hours record maximum compressive strength of the three sets. The MDOT SHA specifications suggest a minimum compressive strength of 4500 psi for the underlay concrete mix, which was attained when the preset time used for steam curing was three (3) hours. This preset time was implemented for steam curing of L-shape underlay samples throughout the entire research and the compressive strength of each batch of concrete mix was measured and reported in the further sections of this report.

5.3 Influence of Formwork Material

The shape of samples and the need for groove pattern on the bond surface of underlay, with grooves of different size and spacing made it necessary to prepare custom-built formwork consisting of individual panels cut out of lumber and Medium-density fiberboard (MDF). The outer shell forming the L-shape was made easy to assemble and remove so as to reuse until the deformations in the panels were more noticeable.

As the L-shape underlay samples were steam cured in oven, few panels in the formwork expand after multiple use and were replaced immediately with new ones. In case of overlay samples, due to curing in moist room the formwork panels absorb moisture and expand, which were eventually replaced with new ones.

Figure 5.3 Formwork for L-shape samples

These groove pieces were initially cut out of Medium-density fiberboard (MDF) and was observed that the moisture in the concrete mix was absorbed by these pieces and grooves were crushed into pieces at the of removing formwork. This resulted in the production of poor quality of grooves that were inadequate to match-cast overlay.

Figure 5.4 Poor Quality grooves on bond surface of L shape underlay due to use of MDF material for formwork panels

The Medium-density fiberboard (MDF) used as a formwork material for preparing grooves on the bond panel was replaced with pieces of hardwood lumber cut to required shape and attached to softwood lumber using nails, resulting in superior quality of grooves on the bond surface of L-shape underlay samples.

Figure 5.5 Superior Quality grooves on bond surface of L shape underlay due to replacing MDF material with hardwood lumber for formwork panels

Figure 5.6 Cut pieces of hardwood used in preparing formwork for grooves on bond surface of L shape underlay sample

5.4 Compressive Strength Results

The compressive strength results were recorded using 4” x 8” cylinders prepared using the same batch of concrete mix as the L-shape sample. In the case of underlay mix, set of 3 cylinders were prepared for each experimental condition and were tested after 18 hours of steam curing. For the overlay mix, set of 4 cylinders were prepared.

The measured compressive strength results at different stages of the L-shape underlay sample subjected to steam curing and the L-shape overlay sample subjected to curing in moist room are shown in Table 5.4. Table 5.4 also gives the calculated averages and standard deviation (Std) of the 28 days strength results. Also the results are plotted in Figure 5.7, Figure 5.8.

Table 5.4 Compressive strength of steam cured L-shape Underlay samples

Compressive strength (psi) of L-shape underlay samples					
Exp. Condition	1	2	3	4	5
After 18 hour steam curing	8064.0	7723.0	7616.4	8847.0	8993.0
	7352.0	8987.5	6823.8	8340.1	8643.3
	8468.0	8740.0	8293.5	8959.0	8540.0
Average	7961.3	8483.5	7577.9	8715.4	8725.4
Std	565.0	670.1	735.6	329.8	237.4

Table 5.5 Compressive strength of Moist cured L-shape Overlay samples

Compressive strength (psi) of L-shape underlay samples					
Exp. Condition	1	2	3	4	5
14 day curing	5284.7	5259.3	5670.0	5156.0	5229.0
28 day curing	5170.9	5426.0	6457.0	5693.5	5196.8
	5255.3	5291.0	5442.2	5662.0	5847.0
	4816.5	5612.8	5785.0	5953.0	5623.0
Average	5080.9	5443.3	5894.7	5769.5	5555.6
Std	232.8	161.6	516.2	159.7	330.3

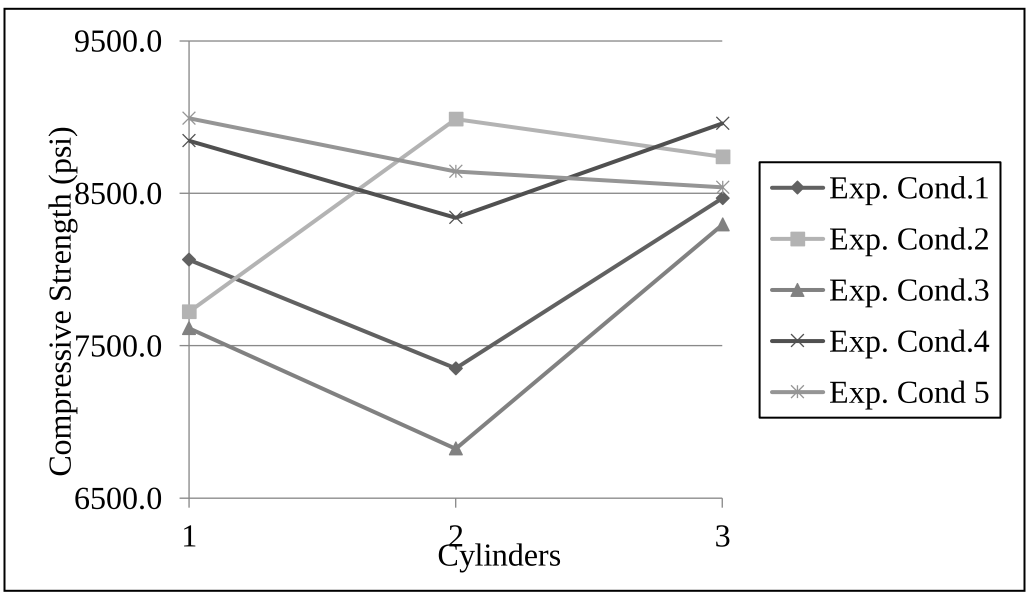

Figure 5.7 Compression Test results from L-shape Underlay Mix with different Experimental Conditions

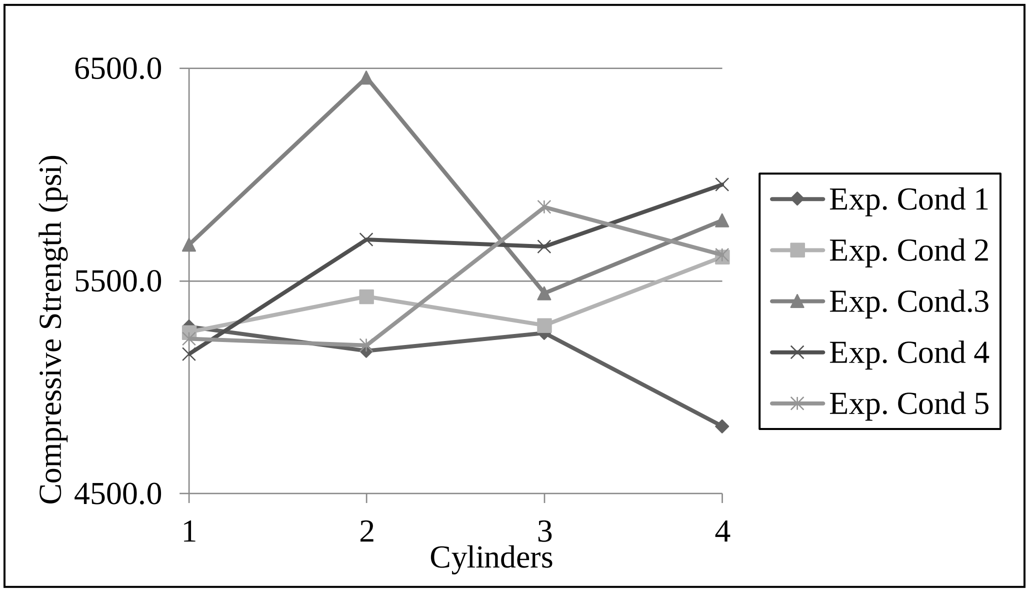

Figure 5.8 Compression Test results from L-shape Overlay Mix with different Experimental Conditions

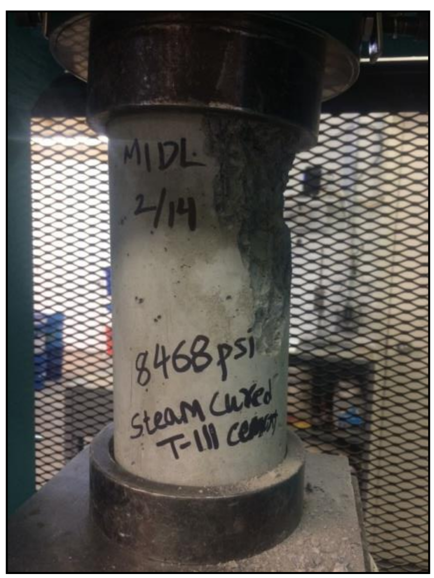

Figure 5.9 L-shape Underlay Cylinder-3 (4" x 8") for Exp. Condition-1 at Failure Compression Load

Figure 5.10 Failure Compression Load recorded on digital display for L-shape Underlay Cylinder-3 (4" x 8") for Exp. Condition-1

In the case of Overlay mix, the 14 day compressive strength was recorded as an additional check for the routine to avoid unexpected delays due to low strength concrete mix. The results indicate that specimens cured using the steam curing regime exhibit the highest compressive strength. A total of 35 cylinders of 4" x 5" size were tested combining all test conditions for the L-shape underlay and overlay samples.

5.5 Shear Bond Strength Results

For each bond surface condition, 4 Double L-shape samples consisting of match cast L-shape overlay with the L-shape Underlay, were used for recording strength of bond between underlay and overlay under shear.

Shear results were collected after specific intervals of curing. The first set of samples in each experiment condition was tested for shear bond strength after 14 days of curing. The 14 day results were recorded to validate the experiment condition and to avoid any unexpected error at the end of 28 days of curing. Table 5.5 also gives the calculated averages and standard deviation (Std) of the 28 days strength results.

Table 5.6 Results from Double L test for Shear Strength of Bond Interface

Shear strength (psi) of bond interface using Double-L samples					
Exp. Condition	1	2	3	4	5
14 day curing	538.5	654.5	730.3	497.5	365.0
28 day curing	653.3	639.0	560.3	743.3	562.0
	671.3	642.0	549.0	558.5	380.0
	646.3	405.0	721.3	380.0	680.0
Average	657.0	645.2	610.2	599.8	540.7
Std	12.9	8.2	96.4	128.0	151.1

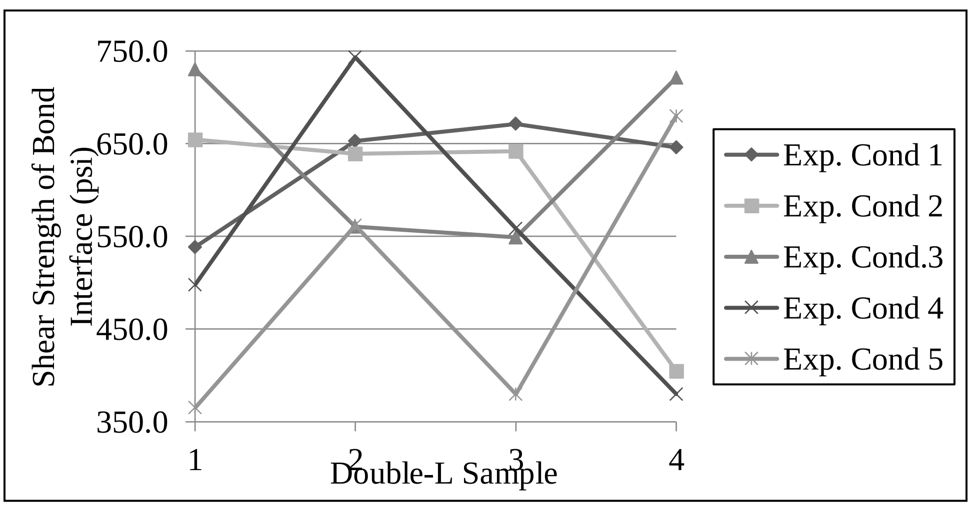

Figure 5.11 Shear Strength results at Bond Interface of Double-L Samples

Figure 5.12 Double-L sample at the beginning of applying shear load

Figure 5.13 Double-L sample at the failure shear load

Figure 5.14 Failure Shear Load recorded on digital display for Exp. Condition-2 of Double L-sample 1

Figure 5.15 Failure plane at bond interface of underlay and overlay for Exp. Condition-3 of Double L-sample 1

In the case of Double-L shear test, the 14 day shear strength was recorded as an additional check for the routine to avoid unexpected delays due to low strength concrete mix. A total of 20 Double-L samples were tested combining all test conditions for the bond interface.

Chapter 6: Split Prism Samples

6.1 Introduction

The potential for deterioration of concrete overlays on the prestressed slab bridges due to weak bond between the overlay and the underlay concrete has been widely recognized in the industry. In this research, five (5) types of bond surface conditions were tested for tensile bond strength using Prism samples. The Prism underlay samples were prepared with Type-III concrete mix and steam cured for 18 hours in a laboratory oven. Along with the Prism underlay samples, 4” x 8” cylinders were prepared to check the compressive strength of each batch of concrete mix.

Table 6.1 Prism Underlay samples prepared

Type	Groove		Underlay samples prepared	
	Depth	Spacing	Prism	Cylinders
1	0.375	1	4	3
2	0.5	1	4	3
3	0.25	1	4	3
4	0.25	0.75	4	3
5*	0.25	1	4	3
		Total	20	15

*Slurry at bond surface

The cylinders were tested for compressive strength before the Prism overlay samples were prepared. The overlay sample was prepared for each type of underlay sample by match-cast technique to achieve the bond at the interface of underlay and overlay. The Split Prism samples resulted from the match-cast of overlay with the underlay were cured in moist room for 28 days. Again 4” x 8” cylinders were prepared along with the Prism overlay samples to check the compressive strength of each batch of overlay concrete mix.

Table 6.2 Prism Overlay samples prepared

	Groove		Overlay samples prepared	
Type	Depth	Spacing	Prism	Cylinders
1	0.375	1	4	4
2	0.5	1	4	4
3	0.25	1	4	4
4	0.25	0.75	4	4
5*	0.25	1	4	4
		Total	20	20

*Slurry at bond surface

Early measurements of tensile strength of the bond were made after curing the Split Prism sample for 14 days. A total of four (4) Prism samples were prepared for each type of bond condition. One of the Split Prism sample in each type of bond condition was tested after 14 days of curing and the remaining three (3) were tested for the tensile bond strength after 28 days of curing in the moist room.

6.2 Influence of Steam Curing

As indicated earlier, throughout this entire research, the concrete mix using ASTM C150 Type-III cement was used for the underlay samples. The underlay Prism samples were subjected to a steam curing regime for quick attainment of the design compressive strength. The Type-III cement has a higher Blaine value; a value that represents the fineness of the cement particles. The increased fineness of the particles allows them to hydrate at a much faster rate and attain up to 70% of the design 28 days strength in less than 24 hours (Lee, C., Lee, S. & Nguyen, N. 2016). The use of this cement type is observed to be a very standard practice in the precast prestressed concrete industry.

Moreover, the use of Type-III cement results in energy conservation during the steam curing process in that it allows same strength development for a reduced temperature and process duration. In the literature, it was found that a maximum temperature between 60ºC and 70ºC and a delay period of three to five hours are optimal values for the steam curing regime. Also, it is proposed that the rate of temperature increase of the specimen should be between 22ºC/hour and 33ºC/hour for optimal strength results without experiencing any excessive volume changes in the specimens (Ramezanianpour, Khazali & Vosoughi 2013).

As for the steam curing regime in this research, the freshly prepared specimen was initially left outside for a preset time of 3 hours. After placing the underlay samples inside the oven, its temperature was increased to 60ºC uniformly at a rate of 20ºC/hour from the ambient temperature. The oven temperature was maintained at 60ºC for duration of 15 hours and was subsequently cooled uniformly to the ambient temperature at 20ºC/hour.

Nine (9) Cylinders of size 4” x 8” were prepared using Type-III concrete mix from the same batch to study the changes in compressive strength of cylinders by keeping all factors similar except the preset time for steam curing. The preset time to gain initial strength was considered as Zero (0) for the first set. The 4” x 8” cylinder samples were prepared and immediately placed in the oven for steam curing following the regime explained earlier. The second set of 4” x 8” cylinder samples were prepared and placed at normal room temperature for 1.5 hours before placing in the oven to start the steam curing regime.

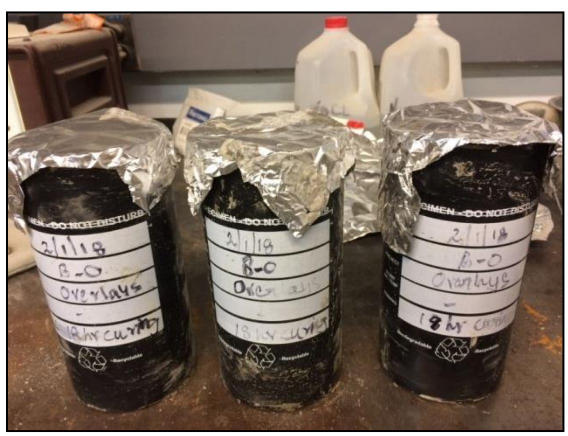

Figure 6.1 Steam curing of 4” x 8” cylinder samples

In the third set the 4” x 8” cylinders were prepared and placed in the oven for steam curing after three (3) hours of preset time. The three set of 4” x 8” cylinders were steam cured with an 18 hour cycle time and allowed to cool to the normal room temperature. The cylinders were then tested for compressive strength attained by the mix using the compressive strength testing machine at NRMCA. The results from the compressive strength test are listed below and are plotted in the Figure 6.2.

Table 6.3 Influence of Preset Time on compressive strength of steam cured underlay cylinders

Cylinder Compressive strength (psi)	Preset time (hrs)		
	0	1.5	3
c1	3480	4326	6500.1
c2	3326.8	4112	6080.5
c3	3841	4203	6237
Average	3549.27	4213.67	6272.53

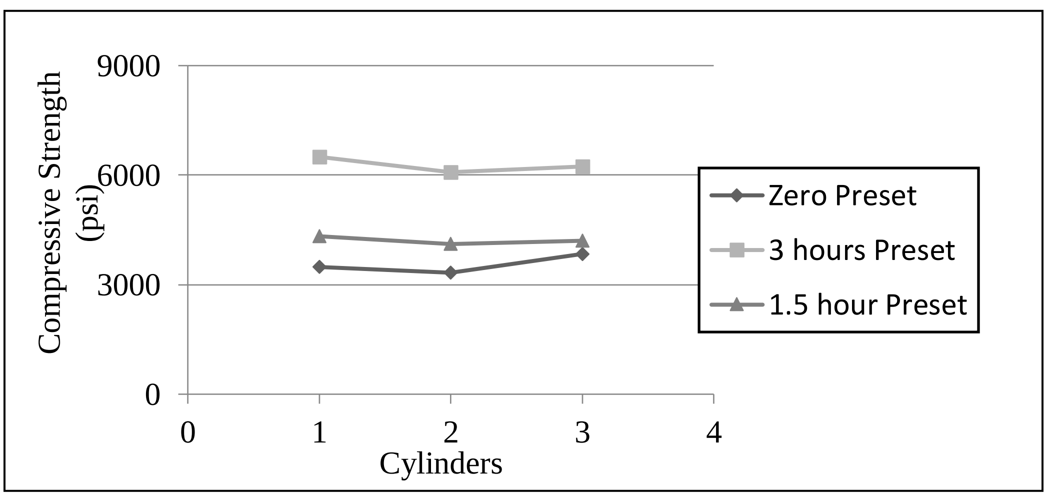

Figure 6.2 Influence of Preset Time on compressive strength of steam cured underlay cylinders of size 4” x 8”

The curves show that the 4” x 8” cylinders steam cured with a preset time of three (3) hours record maximum compressive strength of the three sets. The MDOT SHA specifications suggest a minimum compressive strength of 4500 psi for the underlay concrete mix, which was attained when the preset time used for steam curing was three (3) hours. This preset time was implemented for steam curing of Prism underlay samples throughout the entire research and the compressive strength of each batch of concrete mix was measured and reported in the further sections of this report.

6.3 Influence of Formwork Material

The shape of samples and the need for groove pattern on the bond surface of underlay, with grooves of different size and spacing made it necessary to prepare custom-built formwork consisting of individual panels cut out of lumber and Medium-density fiberboard (MDF). The outer shell forming the Prism was made easy to assemble and remove so as to reuse until the deformations in the panels were more noticeable.

As the Prism underlay samples were steam cured in oven, few panels in the formwork expand after multiple use and were replaced immediately with new ones. In case of overlay samples, due to curing in moist room the formwork panels absorb moisture and expand, which were eventually replaced with new ones.

Figure 6.3 Formwork for Prism samples

These groove pieces were initially cut out of Medium-density fiberboard (MDF) and was observed that the moisture in the concrete mix was absorbed by these pieces and grooves were crushed into pieces at the of removing formwork. This resulted in the production of poor quality of grooves that were inadequate to match-cast overlay.

Figure 6.4 Poor Quality grooves on bond surface of Prism underlay due to use of MDF material for formwork panels

The Medium-density fiberboard (MDF) used as a formwork material for preparing grooves on the bond panel was replaced with pieces of hardwood lumber cut to required shape and attached to softwood lumber using nails, resulting in superior quality of grooves on the bond surface of Prism underlay samples.

Figure 6.5 Superior Quality grooves on bond surface of Prism underlay due to replacing MDF material with hardwood lumber for formwork panels

Figure 6.6 Cut pieces of hardwood used in preparing formwork for grooves on bond surface of Prism underlay sample

6.4 Compressive Strength Results

The compressive strength results were recorded using 4” x 8” cylinders prepared using the same batch of concrete mix as the Prism sample. In the case of underlay mix, set of 3 cylinders were prepared for each experimental condition and were tested after 18 hours of steam curing. For the overlay mix, set of 4 cylinders were prepared.

The measured compressive strength results at different stages of the Prism underlay sample subjected to steam curing and the Prism overlay sample subjected to curing in moist room are shown in Table 6.4. Table 6.4 also gives the calculated averages and standard deviation (Std) of the 28 days strength results. Also the results are plotted in Figure 6.7, Figure 6.8.

Table 6.4 Compressive strength of steam cured Prism Underlay samples

Compressive strength (psi) of Prism underlay samples					
Exp. Condition	1	2	3	4	5
After 18 hour steam curing	8222.0	7198.0	8923.0	7637.1	8317.4
	8428.0	7679.0	8180.0	7542.0	8112.7
	8388.0	8102.6	8245.0	7893.0	8644.0
Average	8346.0	7659.9	8449.3	7690.7	8358.0
Std	109.2	452.6	411.5	181.5	268.0

Table 6.5 Compressive strength of Moist cured Prism Overlay samples

Compressive strength (psi) of Prism underlay samples					
Exp. Condition	1	2	3	4	5
14 day curing	4565.4	5198.0	6102.0	5578.0	6861.2
28 day curing	4843.0	5420.3	6226.6	5827.1	6992.0
	5573.6	5229.0	6493.0	5743.0	7043.0
	5403.3	5512.0	6217.6	6008.1	7127.0
Average	5273.3	5387.1	6312.4	5859.4	7054.0
Std	382.3	144.4	156.5	135.5	68.2

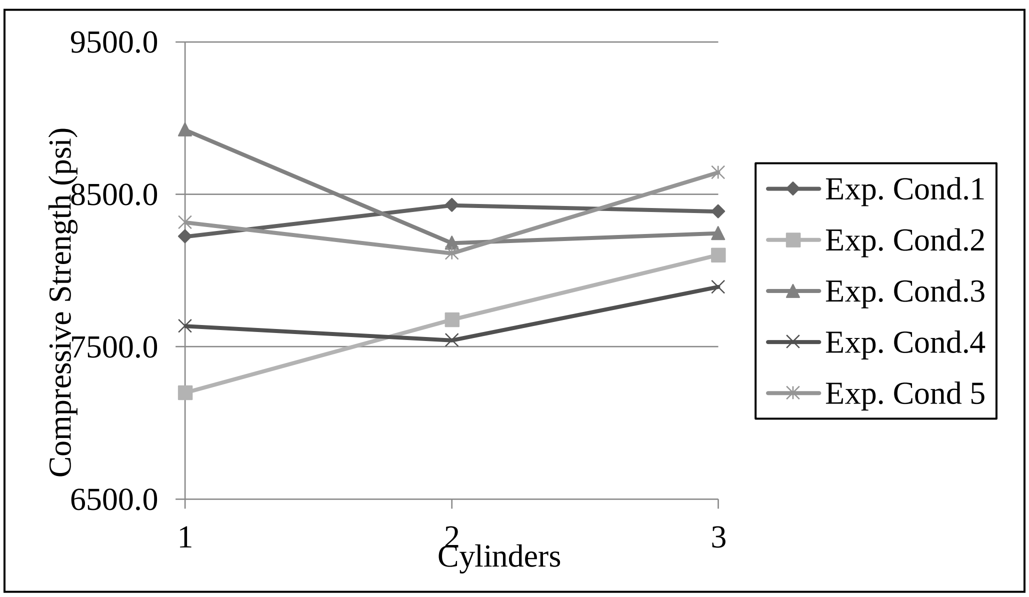

Figure 6.7 Compression Test results from Prism Underlay Mix with different Experimental Conditions

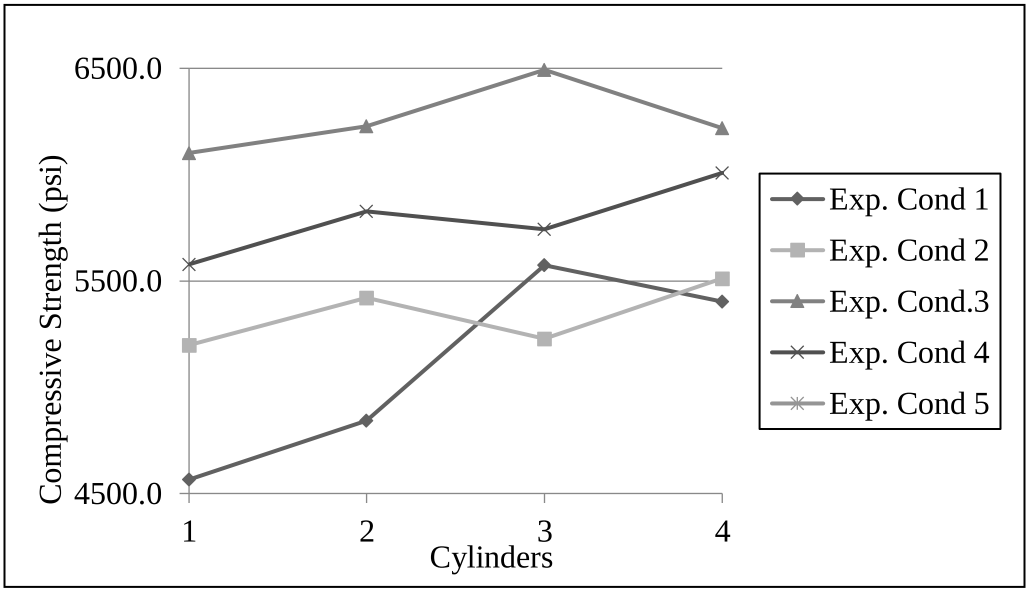

Figure 6.8 Compression Test results from Prism Overlay Mix with different Experimental Conditions

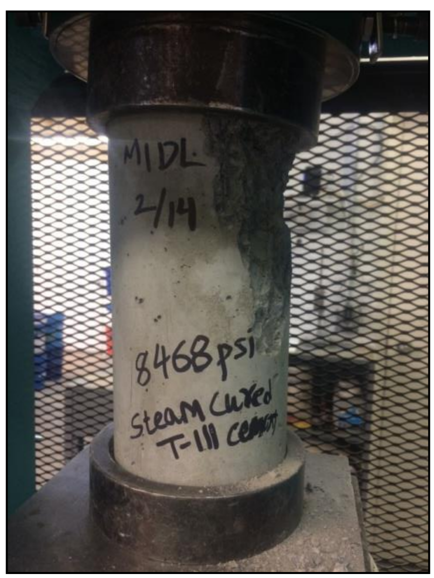

Figure 6.9 Prism Underlay Cylinder-3 (4” x 8”) for Exp. Condition-1 at Failure Compression Load

Figure 6.10 Failure Compression Load recorded on digital display for Prism Underlay Cylinder-3 (4” x 8”) for Exp. Condition-1

In the case of Overlay mix, the 14 day compressive strength was recorded as an additional check for the routine to avoid unexpected delays due to low strength concrete mix. The results indicate that specimens cured using the steam curing regime exhibit the highest compressive strength. A total of 35 cylinders of 4” x 5” size were tested combining all test conditions for the Prism underlay and overlay samples.

6.5 Tensile Bond Strength Results

For each bond surface condition, 4 Split Prism samples consisting of match cast Prism overlay with the Prism Underlay, were used for recording strength of bond between underlay and overlay under Tensile.

Tensile results were collected after specific intervals of curing. The first set of samples in each experiment condition was tested for Tensile bond strength after 14 days of curing. The 14 day results were recorded to validate the experiment condition and to avoid any unexpected error at the end of 28 days of curing. Table 6.5 also gives the calculated averages and standard deviation (Std) of the 28 days strength results.

Table 6.5 Results from Split Prism test for Tensile Strength of Bond Interface

Tensile strength (psi) of bond interface using Split Prism samples					
Exp. Condition	1	2	3	4	5
14 day curing	436.7	277.2	520.0	471.4	630.0
28 day curing	553.3	684.7	529.3	583.5	722.5
	455.8	486.7	485.0	658.9	604.7
	526.9	298.3	228.0	590.5	767.2
Average	512.0	489.9	511.4	611.0	698.1
Std	50.4	193.2	23.4	41.7	62.0

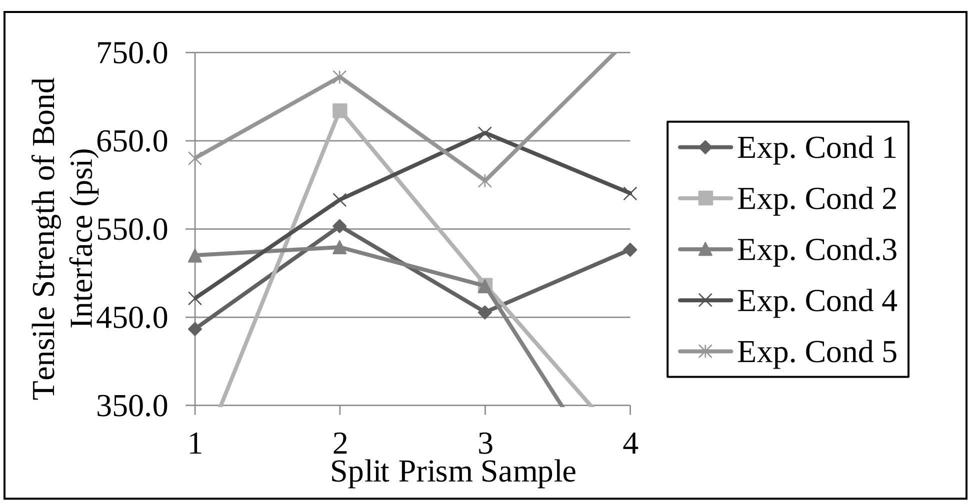

Figure 6.11 Tensile Strength results at Bond Interface of Split Prism Samples

Figure 6.12 Split Prism sample at the beginning of applying tensile load

Figure 6.13 Split Prism sample at the failure tensile load

Figure 6.14 Failure Tensile Load recorded on digital display for Exp. Condition-1 of Split Prism sample 1

Figure 6.15 Failure plane at bond interface of underlay and overlay for Exp. Condition-3 of Split Prism sample 1

In the case of Split Prism Tensile test, the 14 day Tensile strength was recorded as an additional check for the routine to avoid unexpected delays due to low strength concrete mix. A total of 20 Split Prism samples were tested combining all test conditions for the bond interface.

Chapter 7: Summary and Conclusions

7.1 Introduction

The potential for deterioration of concrete overlays on the prestressed slab bridges due to weak bond between the overlay and the underlay concrete has been widely recognized in the industry. Generally, researchers paid little or no attention to investigating the influence of surface preparation on the bond strength between concrete underlay and overlay in prestressed slab bridges.

Researchers often measured the performance of overlays mainly for repair and rehabilitation applications. It is very important to give importance to the surface preparation conditions since it is largely responsible for the performance of concrete overlay. Focus on the surface preparation conditions can provide guidelines to mitigate or prevent tedious and exhaustive methodology for placing concrete overlays.

7.2 Summary

In this research study, laboratory prepared specimens were tested to investigate the influence of surface preparation on bond strength between concrete overlay and underlay. The specimens were prepared using custom built lumber formwork fabricated in-house due to their non-standard shape.

The L-shape and Prism underlay specimens were steam cured for 18 hours to accelerate the process and to replicate the standard practice implemented by the precast slab manufacturers for Maryland State Highway Administration (MDOT SHA). The steam curing was done using the standard laboratory oven available at NRMCA concrete lab. The underlay samples were allowed to cool to room temperature before preparing overlay samples.

The surface preparation was done on the underlay samples by providing different groove pattern on the bond surface. The size and spacing of the square grooves were varied for each case of L-shape and Prism samples. A total of 5 different surface preparation conditions were studied in this research. Before the overlay samples were mast-cast using the underlay samples, the bond surface was cleaned thoroughly using pressurized air and water jet to remove any fine particles of dust at the bond interface. The overlay samples were cured in a moist room for 28 days before the bond strength was measured.

The shear bond strength was tested using Double L samples with load applied as shear on the bond using compression testing machine at NRMCA. The load was applied at a constant rate and the failure was observed as separation at the bond interface of concrete underlay and overlay at the maximum shear capacity value. The figure below shows the failure pattern of the Double L samples tested for shear capacity of the bond.

Figure 7.1 Failure pattern at the bond interface of Double L samples

The results from the Double L shear test including the average values of shear bond strength are tabulated and plotted below. These values were recorded for each surface preparation condition and taken as an average of results obtained from a set of 4 similar samples prepared using concrete mix from the same batch.

Table 7.1 Shear strength (psi) results at bond interface

Shear strength (psi) of bond interface using Double-L samples					
Exp. Condition	1	2	3	4	5
14 day curing	538.5	654.5	730.3	497.5	365.0
28 day curing	653.3	639.0	560.3	743.3	562.0
	671.3	642.0	549.0	558.5	380.0
	646.3	405.0	721.3	380.0	680.0
Average	657.0	645.2	610.2	599.8	540.7
Std	12.9	8.2	96.4	128.0	151.1

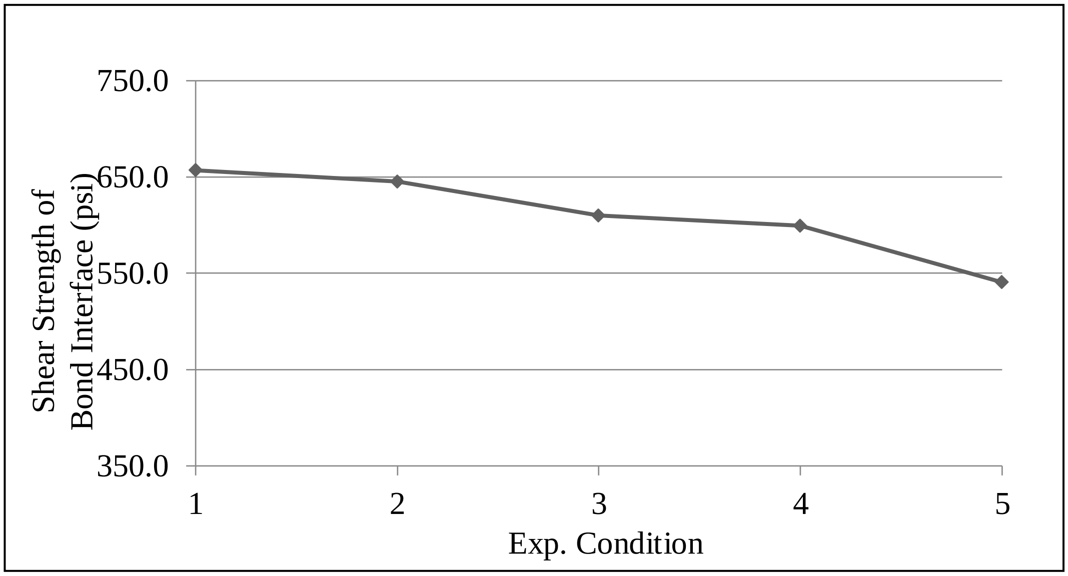

Figure 7.2 Curve showing variation in average shear bond strength values

The tensile bond strength was tested using Split Prism samples with load applied on the bond using compression testing machine at NRMCA. The load was applied at a constant rate and the failure was observed as separation at the bond interface of concrete underlay and overlay at the maximum tension capacity value.

Figure 7.3 Failure pattern at the bond interface of Split Prism samples

The results from the Split Prism Tensile test including the average values of tensile bond strength are tabulated and plotted below. These values were recorded for each surface preparation condition and taken as an average of results obtained from a set of 4 similar samples prepared using concrete mix from the same batch.

Table 7.2 Tensile strength (psi) results at bond interface

Tensile strength (psi) of bond interface using Split Prism samples					
Exp. Condition	1	2	3	4	5*
14 day curing	436.7	277.2	520.0	471.4	630.0
28 day curing	553.3	684.7	529.3	583.5	722.5
	455.8	486.7	485.0	658.9	604.7
	526.9	298.3	228.0	590.5	767.2
Average	512.0	489.9	511.4	611.0	698.1
Std	50.4	193.2	23.4	41.7	62.0

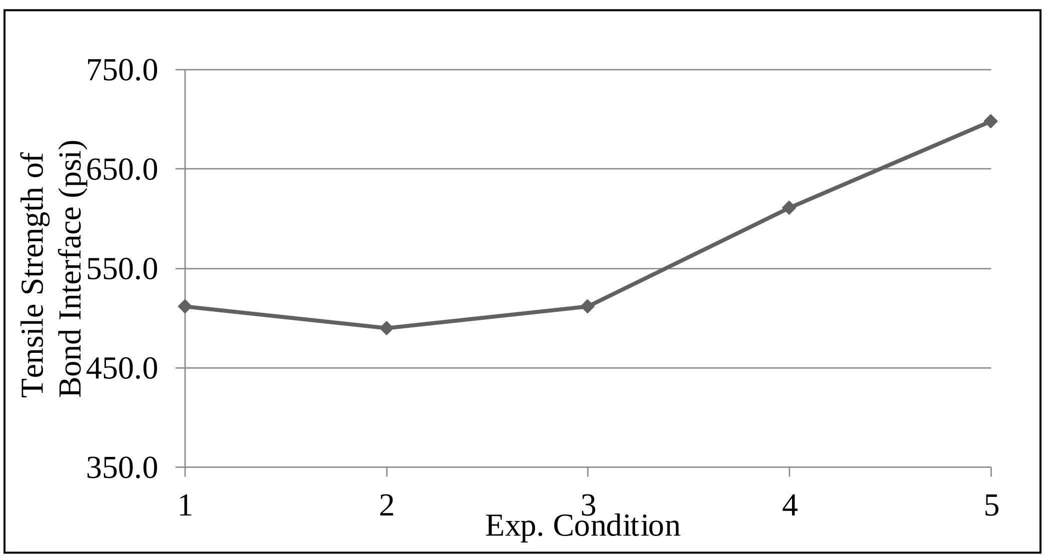

Figure 7.4 Curve showing variation in average tensile bond strength values

7.3 Conclusions

The Based on the laboratory study it is observed that the experimental condition (Exp Condt. 5) with slurry at the bond surface produced minimum shear bond strength compared to all other test cases. The use of slurry at bond surface potentially formed a weak layer and thereby reduced the shear bond strength. The average tensile bond strength values for all experimental conditions are much higher than required value of 233 psi for 20 year performance of overlays (Michael M Sprinkel 1993).

The results from this research suggest that the use of slurry at bond interface during overlay placement can be avoided as better shear bond results were observed in the test cases without the use of slurry. Thus the tedious and exhaustive method of using slurry at bond interface can be replaced by using adequate surface preparation with grooves on the bond surface. The sequence of overlay placement using slurry at bond interface involves the following steps-

Step 1- Tying overlay slab reinforcement

Step 2- Lifting overlay slab reinforcement

Step 3- Cleaning underlay top surface

Step 4- Placing wet slurry mix

Step 5- Lowering overlay slab reinforcement

Step 6- Placing overlay concrete

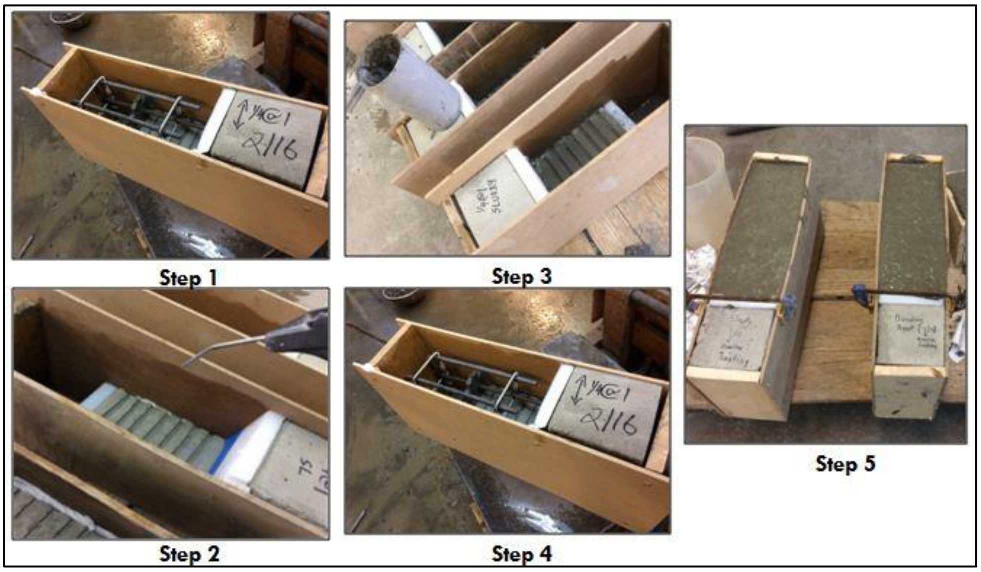

Figure 7.5 Sequence of overlay placement using slurry at bond interface

The sequence of overlay placement without using slurry at bond interface involves the following steps-

Step 1- Tying overlay slab reinforcement

Step 2- Placing overlay concrete

Figure 7.6 Sequence of overlay placement without using slurry at bond interface

7.7 Specimen stacked after testing

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