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**MARYLAND DEPARTMENT OF TRANSPORTATION
STATE HIGHWAY ADMINISTRATION**

RESEARCH REPORT

**BEST PRACTICES FOR PLACING CONCRETE OVERLAYS
ON PRESTRESSED SLAB BRIDGES**

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16. Abstract <p>The objective of this research was to identify alternatives to the Maryland Department of Transportation State Highway Administration's (MDOT SHA) procedure of placing cast-in-place concrete overlays on prestressed bridge decks. The current practice involves the application of a cement-sand slurry mix over the bridge deck prior to placement of overlay concrete. The reinforcement cage for the overlay is removed from its position to facilitate uniform, consistent application of slurry mix over the bridge deck and then subsequently placed back in position. Overlay concrete is then poured to finish the procedure. The current process is time sensitive as it requires that the slurry mix at the deck-overlay interface is in a non-set condition and is still consistent when the overlay concrete is being poured. To evaluate alternatives to this process, this research tested the shear bond and tensile bond strengths by two different test setups: Double-L test and Split-Prism test, respectively. Seven different cases including the reference test case that uses slurry mix were designed for both test setups and the results compared to suggest recommendations for laying concrete overlays in future projects. Of the six cases other than the reference case with slurry mix, four cases simply had different groove configurations running on the underlying substrate. The other two cases involved use of a commercial bonding agent and anchors used as shear studs. Use of materials, mix design specifications, and curing regimes, were in accordance with current MDOT SHA specifications and industry practices.</p> <p>The results of the research on the prestressed slab panels with pre-existing grooves over which the overlay concrete could be directly poured without the need for a slurry or other bonding agents, were very positive. The average bond shear strength values for all the four test cases that have different square-shaped groove configurations (¼ in., 3/8 in. and ½ in. deep grooves at spacing of ½ in. and 1 in.) along the interface were recorded to be higher than the reference test case that uses slurry mix. Based on consultation with the prestressed precast slab manufacturing plants, precast slabs with standard groove configurations could, theoretically, be manufactured at plants for direct use during bridge construction. The overlay concrete could then be directly poured over these panels replacing the current practice. The interlocking effect obtained through the grooves contributed significantly to the bond shear strength and provided good bond characteristics as indicated in the research findings.</p>			
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Executive Summary

The main objective of this research was to identify alternatives to the Maryland Department of Transportation State Highway Administration's (MDOT SHA) procedure of placing cast-in-place reinforced concrete overlays on prestressed concrete slabs. The current practice involves the application of a cement-sand slurry mix over the slabs for small structures over water with spans up to 55 ft. for a single span or, multiple 55 ft. elements for longer bridges, prior to placement of the overlay concrete. The purpose of the slurry mix is to provide a good bond between the prestressed concrete underlay (substrate) and the overlay. To apply the slurry mix, the reinforcement cage for the overlay is removed, the slurry mix is applied, the reinforcement cage is placed back in position, and the overlay concrete is poured while the slurry is still in a non-set condition. This process is cumbersome, inefficient, and highly time sensitive.

The goal of this study was to investigate several alternatives to the current process by evaluating:

- If the slurry is necessary to achieve a good bond between the overlay and the concrete slabs;
- Whether a commercial bonding agent which, can be sprayed on the deck without removing the reinforcing mat, could be used instead;
- Whether stirrups could be added to the slabs that protrude out of the top of the beams by 2 in. at one-foot intervals to lock the overlay with the slab and eliminate the need for the slurry; and
- If there are any other alternatives.

The research team designed and performed laboratory experiments for various test cases with different interface conditions. From the literature reviewed, it was clear that surface roughness and preparation were the most important factors to achieve a good bond between the overlay and the prestressed slab. Seven different test cases were investigated; one of them used, as the reference test case, the application of slurry mix to achieve a good overlay bond. Of the remaining six test cases, four cases involved application of different groove configurations on the substrate to simulate different surface roughness conditions. One case involved the use of commercial bonding agent, *Enecon Superbond*, in addition to grooves, and the last case involved the use of four 6 in. long anchors of ½ in. diameter embedded equally in both layers in addition to the grooves. Use of materials, mix design specifications, and curing regimes for both the underlay and the overlay halves of the specimens were made in accordance to the current practices adopted by the industry and MDOT SHA specifications. Two sets of tests were designed in this study: Double-L test and the Split-Prism test to evaluate the shear bond and tensile bond strengths, respectively. For both tests, precise measurements were made to ensure that the applied load was in line with the bond interface to avoid any additional stresses along the interface due to eccentric loading. All specimens were loaded to failure, and the recorded load values were divided by the interface areas to get the shear bond and tensile bond strengths. In addition, compressive strength tests for each mix were conducted to ensure that the mix strengths were consistent for all test cases. Once the test results were obtained for all the cases, they were compared to the values obtained for the reference test case.

The results of the research on the prestressed slab panels with pre-existing grooves over which the overlay concrete could be directly poured without the need for a slurry or other bonding agents, were very positive. The average shear bond strength values for the four test cases that have different square groove configuration ($\frac{1}{4}$ in., $\frac{3}{8}$ in. and $\frac{1}{2}$ in. deep grooves at spacing of $\frac{1}{2}$ in. and 1 in.) on the underlay substrate were recorded to be higher than the reference test case that used slurry mix. It was found that the interlocking effect obtained through these grooves contributes significantly to the shear bond strength. For the tensile strength tests, the values for the test cases with grooves only are lower than the reference case but are still higher than recommended values by the Virginia (233 psi) (Sprinkel 1993), Oklahoma, New Mexico, (250 psi), and Oregon Departments of Transportation (175 psi) (Appendix A).

Based on these results, the research team recommends the use of prestressed precast slabs with pre-existing grooves, in future projects. The research team consulted with a prestressed precast slab plant and they indicated that manufacturing slabs with pre-existing grooves, is possible. If this recommendation is implemented, the use of slurry mix could be eliminated. This change could result in a significant improvement over the existing practice of using the slurry mix to improve the bond strength of concrete overlays on prestressed concrete deck slabs.

1 Introduction

1.1 Background

To improve the service life of bridge decks, concrete overlays are commonly placed over the deck to provide a riding surface and protect the deck from adverse environmental conditions. Concrete overlays aid in extending the service life of bridge decks by providing a durable, improved frictional riding surface and increasing the load carrying capacity of the deck. They also act as an effective barrier to deicing salt and prevent the corrosion of the reinforcement in the underlying bridge deck due to these salts.

Different types of concrete overlays are commonly used for newly constructed bridge decks and repair of existing decks. Some of the common types are 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 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 states 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. Therefore, the durability of the entire composite system is dependent on the durability of the bond. The bond strength of the interface between the overlay and the bridge deck is an important consideration for the adequacy of these overlays. Due to traffic loading, the interface is subjected to shear and tensile stresses. The bond strength must be adequate to ensure that the desired service life for both the overlays and the bridge deck are achieved.

Currently, state DOTs use various methods to provide good bond characteristics between the concrete overlay and the bridge decks. The methods involve the use of bonding agents such as Portland cement grout, latex modified cement grout, cement slurry, chemical bonding agents and mechanical devices such as shear studs that are embedded in either the overlay or underlay to go through the interface. The use of bonding agents poses a significant challenge during construction as their application is tedious and time-sensitive. For cast-in-place reinforced concrete overlays, this requires the contractor to remove the reinforcement of the overlay after they have been laid out and cut, thoroughly clean the underlying concrete, apply the bonding agent, quickly replace the reinforcement and cast the slab before the bonding agent sets or dries.

Aside from the difficulty and time-consuming nature of using bonding agents, there is some evidence in the literature that questions their usefulness in concrete overlays when proper surface preparation and placement procedures are followed. Bonding agents such as grouts and slurries have higher water-cement ratios, and thus are more permeable. Thus, they may introduce a plane of weakness which can result in lower bond strengths than when no bonding agents are used.

Some researchers are of the view 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).

There is no defined standard method for testing the bond strength of concrete overlays and bridge deck interface. However, a few methods such as shear tests using two L-shaped specimens (Zia et al. 1993), slant shear test (ASTM C 882/C 882M-05), push-off test (Choi et al. 1999) and tensile tests such as the pull-off test (ASTM C1583-04) and split-prism test are considered acceptable for testing the bond strength.

In most studies on bond strength characteristics of concrete overlays to date, different surface roughness techniques have been employed to improve the bond strength and then evaluated using the standard tests available. In this study, the effect of groove patterns with predefined configurations on the bond characteristics—shear and tensile—were studied to evaluate their effectiveness. Four different groove configurations (two groove sizes and two different spacing distances between adjacent grooves) were selected and their effects on improving the bond characteristics were studied in this project. In addition to studying the effect of different surface roughness conditions on the bond strength by altering the groove configurations, the effects of applying a commercial bonding agent at the bond interface and the use of shear studs with equal embedment across both surfaces, were studied.

1.2 Research Problem

In the last few years, the solid prestressed slab span (3 ft. to 4 ft. width pulled together by transverse tensioning rods) has been used by the MDOT SHA's Office of Structures for small structures over water with spans up to 55 ft. for a single span and multiple 55 ft. elements for longer bridges. It is then overlaid with a reinforced concrete deck approximately 5 in. to 8 in. thickness to provide a good riding surface and to protect the many longitudinal plank joints from moisture. When built properly, this combination, solid slabs with concrete overlay, has created the nearest structure possible to a maintenance free bridge. The concrete overlay on the prestressed concrete slab bridges is a critical component. It provides a safe stable surface for vehicles and serves to distribute the loading to multiple prestressed concrete slabs. Before the overlay is placed, to get good adhesion of the overlay to the slabs, the contractor is required to place a layer of concrete slurry worked into the tops of the slabs to aid in developing a good bond. Prior to placing the slurry, the contractor must place all the rebar material on the decks, cut it to fit and totally tie together. Then prior to placing the overlay, the contractor must completely remove reinforcing steel; thoroughly clean the deck, apply the slurry by scrubbing then, while the slurry is in a non-set condition, replace the rebar mat and pour the overlay. This procedure can be difficult especially on long bridges and multi-span bridges, therefore MDOT SHA was interested in investigating whether the slurry is necessary to achieve a good bond, or if there are better alternatives.

1.3 Objectives and Scope

The current practice adopted by MDOT SHA is to use cement slurry as bonding agent for reinforced concrete overlays poured over newly constructed prestressed concrete slabs for bridges. The specifications for surface preparation prior to application of overlay are laid out in the MDOT SHA 2018. *STANDARD SPECIFICATIONS for CONSTRUCTIONS and MATERIALS - 440.03.22.*

The reinforcement cage of the overlay slab should be able to be lifted on and off the substrate structure before placing the overlay. It should be restrained by temporary supports such as diagonal reinforcement bars, or steel angles so that its configuration is not disturbed during the lifting operations. The reinforcement cage is lifted just prior to the placement of overlay concrete and the deck is cleaned thoroughly by employing abrasive blasting. This step is performed no more than 24 hours prior to overlay placement. This is followed by cleaning of the substrate surface by air blasting and subsequent water flushing. The surface is wetted for a minimum period of one hour before laying overlay and it is to be ensured that the concrete deck is not subjected to any additional load(s) other than that due to construction equipment. Misting operations are used to keep the slurry moist as the reinforcement cage for the overlay is carefully placed back in its position, resting on chairs. It must be ensured that the reinforcement is properly laid after levelling the surface. This is followed by placement of concrete mix for the overlay while the slurry is still fluid and has not set.

The current practice of using a slurry mix is very time-sensitive and difficult especially for longer bridges. This study is for new construction of prestressed slab bridges where an overlay is used to create a riding surface and distribute the live load among the various slab units. This research aimed to investigate other possible procedures that can eliminate many of the cumbersome steps in the current process and allow for seamless pouring of concrete overlays in future projects. In this experimental study, the research team performed the following tasks:

- Surveyed current practices used by other State DOTs regarding bonding concrete overlays, specifications, reviewed published literature on field performance, testing methods, etc.
- Investigated bond strength and the performance of overlays that utilized a slurry mix, no slurry mix with groove configurations along the interface, a commercially available bonding agent at the bond interface, and four 6 in. long straight shear studs of diameter ½ in. with equal embedment across the interface in both layers.
- Compared the bond strength and the performance of the specimens for the various test cases listed above with the reference test case employing use of a slurry mix as the bonding grout.
- Recommended specifications and best practices to MDOT SHA for placing cast-in-place reinforced concrete deck on prestressed concrete deck slabs that help in achieving the desired bond strength for the overlays in an efficient and economical manner.

1.4 Research Approach

The MDOT SHA uses a slurry mix for improving the bond strength when constructing cast-in-place concrete overlays for prestressed concrete deck slabs. This is a tedious process as the reinforcement cage for the overlay needs to be lifted prior to application of the slurry, the slurry is poured, then the cage is put back in place and the overlay concrete is poured while the slurry is still in a non-set condition.

This research study aimed to investigate various bonding methods including the current method employed by MDOT SHA. The effects of providing different square groove configurations on the substrate on the bond strength were evaluated. In addition, the effects of using a commercial bonding agent at the interface and shear studs embedded across the interface on the bond strength were analyzed. The research team prepared concrete specimens in the laboratory that simulated the poured concrete overlay and the prestressed deck slabs. The shear bond and tensile bond strengths were evaluated and compared for all test cases. Based on the results obtained, this research aimed to provide recommendations to MDOT SHA to improve their current practice on placing cast-in-place reinforced concrete overlays on prestressed concrete bridge decks when constructing new bridges.

In this project, two different tests were used: the Double-L test for the shear bond strength and the Split-Prism test for the tensile bond strength. For both tests, two identical halves of the concrete specimens are prepared for all test cases: the first half is intended to simulate the behavior of the concrete deck, and the second half that of the concrete overlay. The composite samples are then cured for a period of 28 days under standard curing conditions and finally, tested using the standard compression testing machine apparatus at the laboratory.

For the test cases that didn't use any bonding grout, the research team selected four different square groove configurations that run along the substrate. The configurations were selected based on the literature reviewed and the survey responses received from different state DOTs. The configurations were: $\frac{1}{4}$ in. groove size at 1 in. spacing, $\frac{1}{4}$ in. groove size at $\frac{1}{2}$ in. spacing, $\frac{3}{8}$ in. groove size at 1 in. spacing and $\frac{1}{2}$ in. groove size at 1 in. spacing. A commercial bonding agent, *Enecon - Eneclad Superbond*, was selected for one test case to study the effects of applying a bonding agent on the substrate. To study the effects of providing shear reinforcement across the surfaces, four straight shear anchors manufactured by *Tapcon*, 6 inches long and a $\frac{1}{2}$ inch in diameter, were used for each test specimen for the final test case.

The concrete specimens were prepared with the intention of simulating the behavior of the actual bond as closely as possible. The first halves were prepared using Type-III cement and subjected to 18 hours of steam curing to achieve high early strength. The second halves that represented the concrete overlay were prepared using Type-I cement and the composite specimen was then cured for 28 days under standard curing conditions.

2 Literature Review

2.1 Introduction

Concrete overlays fall in two basic categories: bonded and unbonded concrete overlays. In unbonded 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 that act as one monolithic structure. For bonded concrete overlays to serve its purpose, it must be able to provide a strong bond between the two concrete layers to prevent delamination or debonding.

A complete bond between prestressed slabs and the overlay is critical 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). The bond mechanism depends on the true surface area of contact between the two layers.

Traditionally, bonding agents such 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 cement slurry as the latter 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 agents. 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 used include styrene butadiene (SBR) and acrylics. Epoxy Latex emulsions have also been used as bonding agents; however, their application is difficult and careful consideration must be given to its formulation as it directly affects the bonding agent's 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 this 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). Stirrups, however, do not work until bond has broken, because they must be strained before they can carry any significant load.

There are several issues with using a cementitious bond coat (agent) as used currently by MDOT SHA and other state DOTs. They are very detailed and time consuming to construct due to the

process of removing the reinforcement, cleaning the slabs, placing the slurry, then quickly placing back the reinforcement and casting the slab before the slurry sets. However, there is some evidence that these bonding agents may not be necessary, if proper surface preparation and placement procedures are followed, and the bonding agents might even be detrimental to the bond integrity by introducing another plane of weakness (Silfwerbrand et al. 2011; Trevino et al. 2003).

2.2 Practices to ensure good bond between the substrate and overlay

A strong, durable bond between the substrate concrete and the overlay is the most important factor for the reliability of the structure. Silfwerbrand et al. (2011) argue that a durable bond in concrete overlays can be achieved if all operations for concrete removal, surface cleaning, concrete placing, and curing are done carefully with attention to details. The substrate 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 and a dry substrate surface prior to overlay placement is best for achieving good bond strengths. It is recommended that the substrate surface be cleaned twice – the first time, immediately after water jetting and the second, before laying the overlay concrete.

Talbot et al. investigated the influence of different interface textures and concluded that smooth as well as sandblasted surfaces experienced a significant loss of bond strength with time. However, surfaces that 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 substrate surface induces cohesion by the interlocking effect. Workability and proper compaction of the mix of the freshly placed overlay ensures that the cavities and voids on the substrate concrete surface are properly filled. The Swedish National Road Administration recommends the use of vibration pokers and vibration platforms to achieve proper compaction (Silfwerbrand et al. 2011). Self-consolidating materials (with high workability) are expected to lead to a higher effective contact area and a higher bond strength. Properties of the hardened overlay material also influence the bond properties. It was 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 substrate cannot migrate through the overlay. The bond strength is also a function of the substrate surface temperature. Cold substrate (at 39°F) results in a lower initial bond strength but higher long-term bond strength in comparison to substrates at higher temperatures (70°F or 100°F). Grouting material such as a cement-sand slurry mix between prestressed concrete slabs and cast-in-place overlays has also been used in some practices.

2.3 Factors influencing bond strength

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 at the interface, and mechanical crossing devices across the interface. Of all the factors that influence bond strength, surface preparation and cleaning of the substrate concrete are the most important. The following sections discuss in detail, the different factors that affect the bond strength at the interface.

2.3.1 Bond surface conditions

In the MDOT SHA's current practice, the substrate surface is raked prior to the curing of the prestressed concrete slab units. This allows the substrate surface to develop a certain roughness that aids in better interlocking and bond strength at the interface. Silfwerbrand et al. (2011) argue that the bond strength, up to a certain threshold surface roughness, increases and then levels out. This threshold surface roughness can be provided by sandblasting the substrate surface, which also helps in clearing the accumulation of fine particles on the surface of fresh concrete; it is a potential weak zone and is susceptible to a quick failure.

2.3.2 Slurry/Overlay bonding grout

The specification for laying the slurry mix are in accordance to clause 440.02.05 of MDOT SHA manual STANDARD SPECIFICATIONS for CONSTRUCTION and MATERIALS, 2018. To prepare the slurry, equal parts by weight of Portland cement and sand are mixed with sufficient water to produce a slurry. The consistency of the mix must allow for application of the mix with a stiff brush or broom in a thin, even coating that will not run or puddle. Similarly, the state of Indiana spreads a slurry coat of the same material as the overlay on the cast in place decks of the bridges before applying an overlay.

2.3.4 Shear Studs

Missouri DOT uses a mechanical bond (reinforcement) between the overlay and the precast element. Silfwerbrand et al. (2011) stress that the reinforcement should be sufficiently anchored in both layers – overlay and the substrate. In this study, the mechanical bond between both layers is developed by using straight anchors of 6 in. length and ½ in. diameter manufactured by *Tapcon*. The embedment of these anchors is kept identical (3 in.) across both layers.

2.3.5 Use of chemical adhesives

Bonding agents are usually employed to improve the bond strength of the interface between the two layers. This helps to improve the cohesion and integrity of the bond between the two surfaces. If the bond between the substrate and the overlay is not durable, water and de-icing salts may seep through the overlay to the substrate deck due to the poor adhesion and affect the structural strength of the underlying slab unit. It is imperative that the substrate layer is treated properly and cleaned of any dust and/or unsound concrete particles before application of suitable bonding agent (Silfwerbrand et al. 2011).

Studies have shown that the use of bonding agents cannot compensate for poor surface treatment. Moreover, it requires very careful attention and can instead act as bond breakers if not used properly. Grout has a higher water-cement ratio that reduces the bond strength and induces the risk of cohesive failure within the bonding agent itself. Methods like scarifying and acid etching are used to create grooves to prepare the surface for receiving the overlay.

The two standard types of bonding agents commonly used in the construction industry are latex emulsions and epoxies. Latex emulsions consist of high water content and suit cementitious compositions. It is recommended that some cement material be used with latex to avoid the formation of a film in the bonding layers that can result in a potential failure plane. Of the different commercial bonding agents available in the market, four widely used products were reviewed in this report. These bonding agents serve in providing an effective bond between the substrate and the overlay.

Euclid Chemical – Dural Prep AC: It is an in-situ (natural) bonding agent with an anti-corrosion coating for the reinforcement steel. This product is a water-based epoxy-bonding agent and can be combined with Portland cement to create the bonding agent for placing the fresh concrete over the substrate material. The open time for this product is 20 hours at 90°F (32°C), 24 hours at 75°F (24°C) and 30 hours at 45°F (7°C).

Edison Coatings, Inc. – Flexi Bond 540: This 100 % solid epoxy bonding agent and primer can assure effective bond between the concrete substrate and the concrete overlay. The open time for this product is 24 hours.

Sika – Armatec 110 EpoCem: It is a three component, solvent free, moisture tolerant, epoxy modified, cementitious product specifically formulated as a bonding agent and anti-corrosion coating. The working time is 90 minutes and has a 24-hour open time for application of the concrete overlay.

Enecon – Eneclad Superbond: It is a 2-component polymer composite bonding agent to serve as a bond coat for concrete overlay on top of the substrate. The product has an open time of 24 hours.

A bonding agent ultimately acts as a product that can join the overlay and the precast element so that there is no requirement for mechanical fastening. However, it should be noted that improper application of the bonding agent can lead to two possible planes of weakness.

2.4 Steam-curing process

In this study, ASTM C150 Type III cement used for the underlay part is subjected to a steam-curing process to quickly achieve design compressive strength. Type III cement has a higher Blaine value which implies a greater fineness of the constituent cement particles. The increased fineness of the particles allows the cement to hydrate at a much faster rate and attain up to 70% of the design 28-day strength in less than 24 hours (Lee, C. et al. 2016). Moreover, the use of Type III cement results in energy conservation during the steam-curing process as it allows the

same strength development at a reduced temperature and process duration. The use of this cement type is a standard practice in the precast and prestressed concrete industry.

In the literature, it was found that a maximum temperature between 140°F (60°C) and 158°F (70°C) and a delay period of three to five hours were optimal values for the steam-curing process. Also, it is proposed that the rate of temperature increase of the specimen should be between 40°F/hour and 60°F/hour for optimal strength results without experiencing any excessive volume changes in the specimens (Ramezani pour et al 2013; Gurley, E. 2011).

2.5 Materials for overlays

Silfwerbrand et al. (2011) stress the importance of the workability and compaction of the overlay concrete to achieve good bond strength. A fluid mix fills the open cavities on the substrate surface, increasing the effective contact area at the interface. A concrete that has self-consolidating properties is very helpful to develop good interfacial bond strength. In addition, the authors argue against the use of impermeable overlay material as it does not allow moisture to escape the substrate material, causing additional stresses at the interface. Many studies also conclude that the overlay should ideally be laid on a substrate surface that is saturated surface dry (SSD), the condition of an aggregate in which the surfaces of the particles are "dry" (i.e., surface adsorption would no longer take place), but the inter-particle voids are saturated with water. A study by the Swedish National Road Administration (Silfwerbrand et al. 2011), recommended that the overlay concrete be properly compacted to avoid development of any air pockets in the grooves of the substrate surface. To achieve proper compaction, use of vibrating pokers and vibration platforms was recommended.

The concrete mix design used for the underlay half was consistent with the specifications in use by the precast plant manufacturing slabs. Similarly, the concrete mix design for the concrete overlay conforms to the specifications of the MDOT SHA manual *STANDARD SPECIFICATIONS for CONSTRUCTION and MATERIALS, 2018*. The proposed maximum size for the coarse aggregates is ½ inch. This was, also, consistent with the responses received from various state DOTs in the survey conducted by the research team. In contrast, the state of Oregon, for example, recommends maximum aggregate size of ¾ inch.

The use of some other materials for concrete overlays was made by a few state DOTs. For instance, New Mexico recommends use of polyester concrete overlay (*Kwikbond*, for example) for constructing and repairing bridge decks. The Indiana DOT, on the other hand, recommends use of latex modified concrete as the overlay material. The specifications for laying the overlay are in accordance with clause 722.09 of the manual *Standard Specifications, 2014, Indiana Department of Transportation*.

2.6 Testing of bond between overlay and substrate

Several test methods and formats have been developed for testing interface bond strength of concrete overlays. At the interface between the 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 depend on specimen size, test format, loading rate and whether the test is performed in-situ (in nature) 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 the most popular test in this category and is the easiest to perform. 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 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 the 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 rarely exists in construction (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. They achieved consistent results for bond strength on commonly used overlay materials, however there were issues with rotation of the 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 the wide variability of test formats in the literature, a comprehensive study of different types of bond strength tests was performed to select the 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.

2.6.1 Double-L test

In research conducted under the *Strategic Highway Research Program (SHRP)*, an experiment was done to determine the interfacial bond strength of two concrete layers using a Double L Test (Figure 1) (Zia et al. 1993). In this method, two L-shaped concrete specimens are used: one cast using Type III cement and subjected to steam-curing process to simulate the action of the prestressed underlay slab; and the second specimen that represents the overlay slab is cast using Type I cement and cured for 28 days under standard curing conditions. They are bonded face-to-face as shown in Figure 1. This method allows for the prediction of the behavior of the concrete overlay on the new or existing prestressed concrete bridge deck.

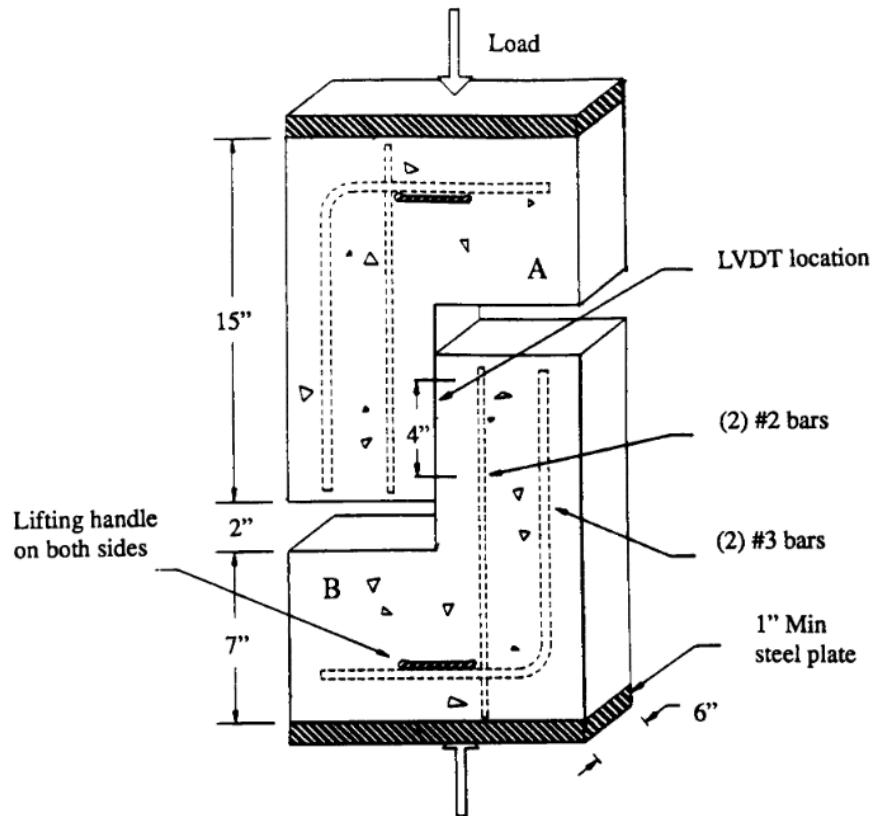


Figure 1: Typical test setup for the Double-L test (Zia et al. 1993)

Both the underlay and the overlay halves are provided nominal steel reinforcement to ensure that the composite specimen fails in shear along the interface. In this format, it is very critical that the line load from the test machine coincides with the interface plane to ensure zero or minimal eccentricity so that the failure plane is in a condition of direct shear.

In this research study, the Double- L test was chosen for testing the shear bond strength of the concrete overlays with the substrate. Two L-shaped segments with dimensions of 14 in. x 10 in. x 5 in. were chosen with each segment reinforced with two straight No. 3 bars and two L-shaped No. 3 bars. In addition, two ¼ in. diameter square ties were provided to hold the main reinforcement bars in place along the 14 in. edge direction for each segment.

The specimen was placed on the testing machine and the load value at failure was noted. The failure load was divided by the area of the bond interface to compute nominal bonding stress. In this case, the nominal bonding area was equal to 40 square inches.

2.6.2 Slant Shear Test

The slant shear test (Figure 2) 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. An epoxy system is used to bond together two identical cylindrical sections of 3 in. by 6 in. The bonding area is an

angle of 30° to 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 $73 \pm 2^\circ\text{F}$ 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, the area of the bonded area used in preceding calculations is reduced to account for these voids. In this reduction, neglect any voids that are not larger than $\frac{1}{8}$ inch.

Several researchers have indicated that this test has shortcomings due to unrealistic loading conditions (Silfwerbrand et al. 2011), while others have highlighted its sensitivity to the surface roughness of the underlying concrete (Júlio et al. 2004), an essential component of bond strength. In the slant shear tests, significant coefficients of variations were observed between the different surface roughness conditions such as wire-brushing, partially chipped, partially chipped & pre-wetted and sand-blasting (Júlio et al. 2004).



Figure 2: Slant Shear test format

2.6.3 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 (Figure 3) 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 (low carbon) 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 layout,

there was a small eccentricity of 0.78 in. (20 mm) because the centerline of the steel bars was not right at the interface, but they considered this moment to be negligible.

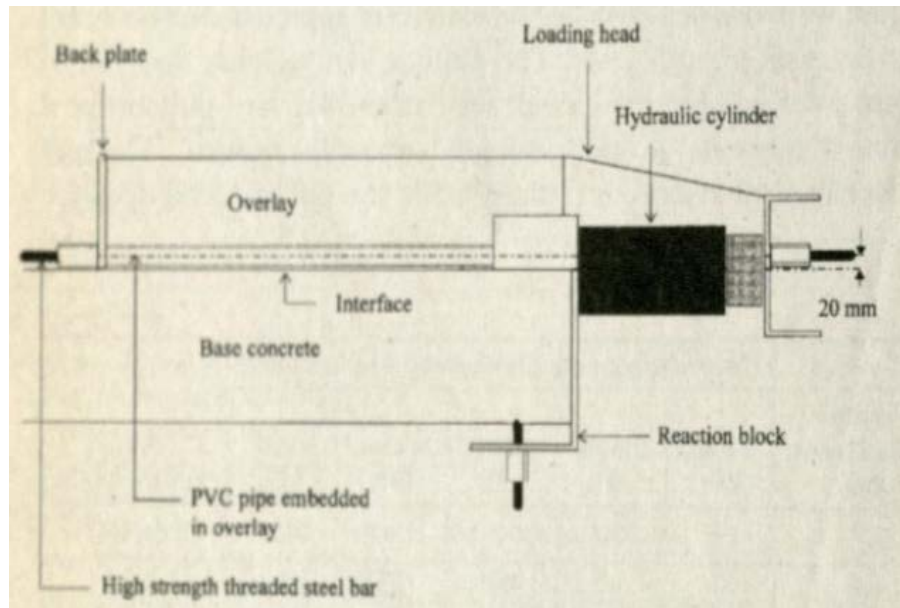


Figure 3: In-situ push off test: alignment of interface and hydraulic cylinders (Choi et al. 1999)

This test is very sensitive to the surface roughness of the interface. In the test layout, heavily shot-blasted surfaces experienced no significant relative slip at the interface until the peak load of 18,210 lbf (pound-force) (81 kN (kilonewton)); the displacement was 0.01 in. (0.3 mm). On the contrary, in the case of lightly shot-blasted surfaces, the overlay started slipping when the shear load reached half of the peak value of 15,737 lbf (70 kN). Displacement of 0.04 in. (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 0.39 in. (10 mm).

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-strength 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 uncracked specimens.

2.6.4 Split-Prism Test

The Split-Prism test (Figure 4) is a standard test for quantifying tensile strength of prismatic concrete specimens. It is also known as the splitting tensile test. In the experimental setup for this study, two halves of a split prism, one cast with Type III cement and subjected to steam-curing

and the second cast with Type I cement subjected to normal moist-curing, were used. The size of each half in the specimen was 6 in. x 6 in. x 3 in.

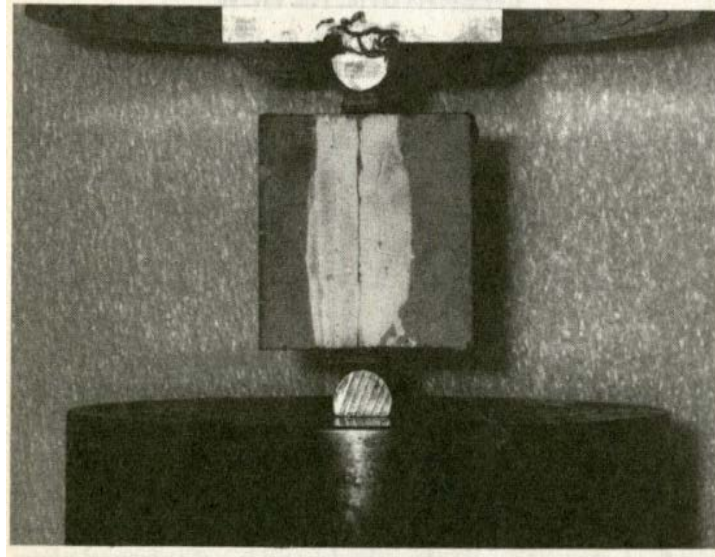


Figure 4: Split-Prism test format

2.6.5 Pull-off test

The pull-off test (Figure 5) 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 then 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.

To prepare the test specimen, at least 0.39 in. (10 mm) depth of the specimen below the concrete-overlay surface is drilled. The surface must be free of any standing water and cleaned of any debris. An epoxy adhesive is used to attach the steel plate to the top face of the specimen. The tensile load is applied at the standard constant rate (as indicated in ASTM C1583) concentric to the plate and the specimen 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. The load is then divided by the bond surface area to compute the tensile bond strength.

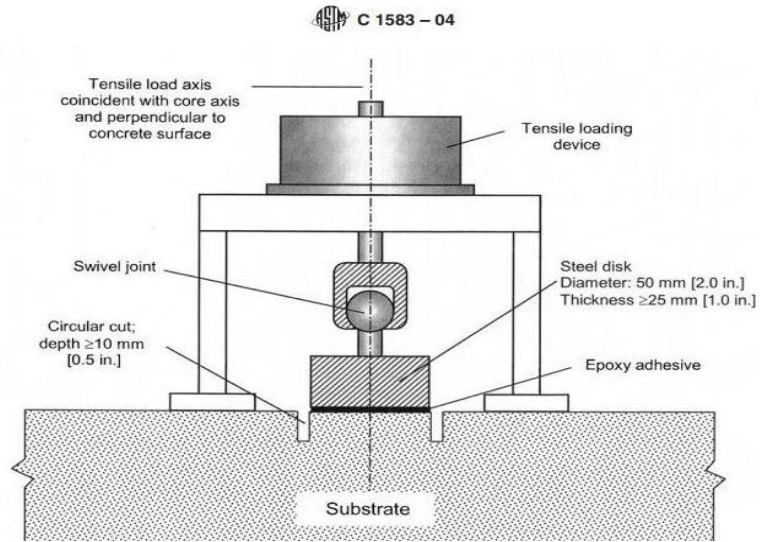


Figure 5: Pull-off test setup for checking tensile strength of substrate (ASTM C1583)

3 Methodology

3.1 Introduction

For this research project, two different sets of specimens were prepared for the Double-L and the Split-Prism test layouts. As discussed before, for both specimens, underlay and overlay halves were prepared to simulate the action of the underlying slab and the concrete overlay, respectively. For the Double-L test, an L-shaped underlay half was prepared over which the concrete overlay was poured to get a composite cuboidal specimen. Similarly, for the Split-Prism test, a 3 in. x 6 in. x 6 in. cuboid underlay half was prepared with the concrete for the overlay poured on its side to get a composite 6 in. cube specimen.

3.2 Materials

3.2.1 Formwork

Due to the unconventional shape of the concrete specimens, custom formwork was prepared using wood panels. Two different types of wood panels were used: a $\frac{1}{4}$ in. thick medium-density fiberboard panel and a $\frac{3}{4}$ in. thick conventional wood lumber. The lumber was marked, and panels were cut from it to the appropriate dimensions using a table saw. The assembled formworks for both test configurations are shown in Figure 6.

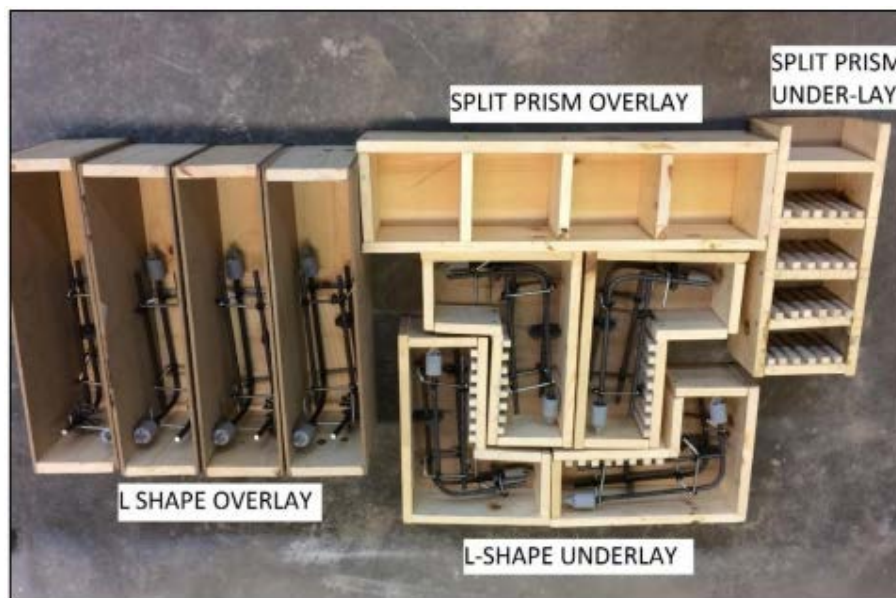


Figure 6: Assembled formwork for different concrete specimens

3.2.2 Cement

Portland cement was used for preparing the test specimens. For the underlay half, Type III cement as per ASTM C150 is used; the use of this cement type, in conjunction with the steam-curing process, helps in accelerated strength development. For the overlay half, per ASTM C150 Type I cement was used. The use of the respective cement types was done to closely simulate the actual field conditions. The use of Type III cement is very common in plants manufacturing precast prestressed slabs to achieve high early strength and for a quick manufacturing turnaround period. Similarly, cast-in-place concrete overlays commonly use Type I cement for the concrete mix.

3.2.3 Coarse Aggregates

Per the AASHTO M 43 specification, No. 8 stones were used as coarse aggregates for the concrete mix. A sieve analysis of a representative sample of the coarse aggregates was performed; the results were as indicated in Table 1 below. The use of this gradation allowed for a good, workable mix and allowed for a proper, consistent concrete flow inside the grooves, especially in the congested space around the reinforcement for the L-shaped specimens.

Table 1: Results for sieve analysis of coarse aggregates

Sieve Size	1 in.	¾ in.	½ in.	⅜ in.	No. 4	No. 8
Weight retained (lb.)	-	-	0.10	2.10	7.51	1.03
Weight of aggregate finer than (%)	100	100	99.09	80.02	11.88	2.56

To account for the effect of surface moisture on the coarse aggregates in the concrete mix design, dry-oven tests were carried out to compute the surface moisture content of the aggregates. Over the course of this research study, the moisture content remained very consistent and the same value was used throughout for all mix designs.

The results for the moisture content for the coarse aggregates as computed from the dry-oven test were as indicated in Table 2 below.

Table 2: Results for the dry-oven test for coarse aggregates

Weight of sample (lb.)	11.02
Dry weight (lb.)	10.97
Moisture content (%)	0.452

3.2.4 Fine Aggregates

Manufactured sand acquired from one of the nearby quarries in Maryland was used as the fine aggregates in the concrete mix design. As observed for the coarse aggregates, the moisture content of the fine aggregates remained consistent over the course of this research study. Table 3, below, shows the results obtained for the moisture content obtained from the dry-oven test.

Table 3: Results for the dry-oven test for fine aggregates

Weight of sample (lb.)	11.02
Dry weight (lb.)	10.67
Moisture content (%)	3.29

3.2.5 Admixtures

Two admixtures were used in the concrete mixes for preparing the specimens. To meet the MDOT SHA specifications, the air-entraining admixture, *Sika AEA-14*, was added to ensure sufficient air-entrainment. This admixture was added to water prior to its addition to the mix design constituents. Secondly, the water reducing admixture, *Sika ViscoCrete-2100*, was used in different doses for the underlay and the overlay halves to correspond to the required workability of both mix designs. The dose was higher for the underlay half due to two factors: the use of Type III cement that made the mix very stiff, and the requirement of a lower water-cement ratio for this mix. The admixtures used are shown in Figure 7 below.

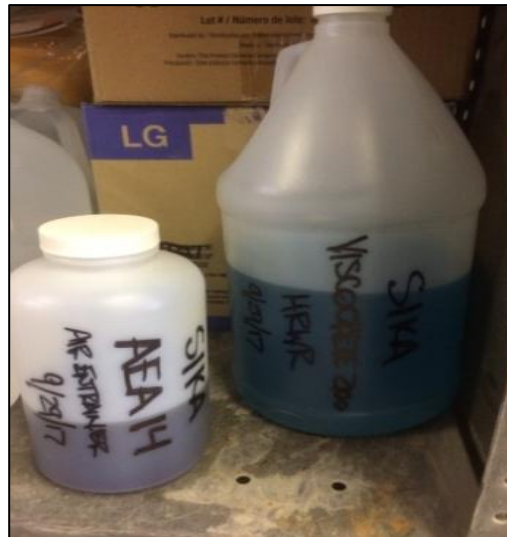


Figure 7: Admixtures – Sika AEA-14 and Sika ViscoCrete-2100

3.3 Mix Design

The mix design specifications for preparing the underlay halves of the test specimens were chosen in consultation with Northeast Prestressed Products, LLC plant in Cressona, Pennsylvania. The specifications allow for the rapid development of concrete strength due to the use of ASTM Type-III cement and an 18-hour steam-curing process. The mix design specifications adopted for the underlay concrete were as indicated in Table 4.

Table 4: Mix design specifications for the underlay mix

Type of Cement: <i>ASTM Type-III cement</i>
Fine Aggregates: <i>Manufactured Sand</i>
Coarse Aggregates: <i>No. 8 stone (AASHTO M 43)</i>
Water-Cement Ratio: <i>0.34</i>
Air-entraining admixture: <i>SIKA AEA-14 – The dosage adopted was 2.5 fl. Oz per 100 lbs. of cement to entrain 5.5% of air in the mixture.</i>
Plasticizer: <i>Sika ViscoCrete-2100 – Dosage was adjusted to achieve desired mix workability.</i>

The target slump value for the underlay mix was set at eight (8) inches. In the trial mixes, it was observed that rapid hardening of Type-III cement along with a reduced water-cement ratio led to a very stiff concrete mix. This caused difficulties in working with the mix and properly filling the grooves on the bond panel. To overcome this issue, the dose of the plasticizer was adjusted accordingly to achieve a workable mix to fill the grooves.

The preparation of underlay specimens for any given case (of the seven tested cases) comprised of two different mixes. The first mix included four L-shaped specimens and three 4 in. x 8 in. standard cylinders. The second mix included four 3 in. x 6 in. halves of split-prism specimens and three 4 in. x 8 in. standard cylinders.

After using the above specifications for the underlay mix design, the average cylinder strength observed after treating the samples to an 18-hour steam-curing cycle was nearly 8500 psi.

The mix design specifications for the overlay concrete pour were as indicated in Table 5.

Table 5: Mix design specifications for the overlay mix

Type of Cement: <i>ASTM Type-I cement</i>
Fine Aggregates: <i>Manufactured Sand</i>
Coarse Aggregates: <i>No. 8 stone (AASHTO M 43)</i>
Water-Cement Ratio: <i>0.38</i>
Air-entraining admixture: <i>SIKA AEA-14 – The dosage adopted was 2.5 fl. Oz per 100 lbs. of cement to entrain 5.5% of air in the mixture.</i>
Plasticizer: <i>Sika ViscoCrete-2100 – Dosage was adjusted to achieve desired mix workability.</i>

The mix design for preparing the overlay halves for all test specimens also comprised of two different mixes. The first mix involved pouring of overlay concrete for the four L-shaped underlay halves and casting of four 4 in. x 8 in. cylinders. The second mix involved pouring of overlay concrete for the four 3 in. x 6 in. underlay halves of split-prism specimens and casting of four 4 in. x 8 in. cylinders. The weight and volume of all constituents for the different mix designs are indicated in Table 6.

Table 6: Mix design specifications for the four mix types

Mix	L-shaped underlay sample	Split-prism underlay sample	L-shaped overlay sample	Split-prism overlay sample
Cement (lbs.)	66.2	26.5	59.3	23.7
Coarse Aggregates (lbs.)	98.1	36.8	98	36.8
Fine Aggregates (lbs.)	52.5	21	58.5	23.4
Water (gal)	2.59	1.04	2.58	1.03
SIKA AEA-14 (gal)	0.0124	0.0048	0.0111	0.0042
Sika ViscoCrete-2100 (gal)	0.0169	0.0066	0.0079	0.0026

Slump tests were performed for all concrete mixes for both the underlay and the overlay pours, and the slump values were found to be in the acceptable range. The dosage for the plasticizer (Sika ViscoCrete) needed to be adjusted accordingly for a few mixes to achieve required workability and corresponding slump values.

3.4 Sample Preparation

3.4.1 Underlay Samples

For preparing the underlay halves of the test specimens, fabrication of custom formwork was required given the unconventional shapes of the concrete specimens. Strips were cut precisely using a table saw and hammered on the inside of the bond panel for obtaining the square groove patterns on the finished underlay substrate. The cut panels were then screwed together at the lab.

Square groove patterns of different widths – ¼ in, ⅜ in. and ½ in., were required for the different test cases described in Table 8 (on page 34). For the initial trials, strips were cut from medium-density fiberboard panels. However, due to their tendency to absorb water from the mix, they were discontinued and were replaced with hardwood lumber for the actual experiments. Also, it was observed that the medium-density fiberboard strips required more frequent replacement as they would expand during steam curing resulting in some deterioration of the finished grooves. In Figure 8, freshly poured underlay specimens are shown and the steam-cured, demolded underlay half is seen in Figure 9.



Figure 8: Freshly poured underlay concrete specimens



Figure 9: L-shaped underlay half after 18 hours of steam curing

For the shear bond strength test on the L-shaped specimens, it was critical to ensure that failure occurs at the bond interface. If the standard testing procedure is followed where the centerline of the load is along the bond interface, this condition will be met. Nominal reinforcement is provided along the two legs of the specimen to avoid any cracking of specimen before reaching the bond failure. This is particularly important for the shorter horizontal leg of the specimen which effectively acts as a cantilever while the load is applied and is susceptible to cracking if there were no reinforcement bars.

For each half of the L-shaped specimen, four (4) #3 bars were provided as reinforcement. Two of the bars were straight bars that ran along the longer side and the other two were L-shaped bars that also ran along the longer side but turn to also act as the top reinforcement bars for the shorter cantilever portion of the specimen. The bars helped ensure adequacy against possible concrete cracking and ensure that the results reflected the shear bond strength of the bond interface.

In addition to the main reinforcement bars, two sets of ties were provided for each specimen, primarily to ensure that the main bars were held in place. The ties were $\frac{1}{4}$ in. diameter bars, the small diameter allowed for bending into an approximately 3 in. x 3 in. square for use as ties. They are bent using a hollow square metal rod. Figure 10 shows a tied reinforcement cage assembly.



Figure 10: Reinforcement cage for the L-shaped halves

For the test case that involved the application of the bonding agent on the underlay substrate, commercial bonding agent *Enecon-Eneclad Superbond* was selected for use. The specifications, as provided by the vendor, are indicated below:

- Coverage rate per kg = 40-45 ft² (4 m²)
- Mixing ratio of base to activator (by weight) = 10:1

The above specification was duly followed while applying the product at the interface of the underlay specimen prior to pouring of overlay concrete.

To ensure that the bond interface surface was free of any dust or loose particles, the surface was cleaned by air blowing and a subsequent application of acetone over it. The two constituents of the bonding agent (base and activator) were mixed thoroughly for 2-3 minutes prior to its application on the interface using a stiff brush. An underlay half for a Double-L specimen with the bonding agent applied on the substrate can be seen in Figure 11. Following the application of the bonding agent, overlay concrete is poured over the underlay half placed in the cuboidal formwork (Figure 11).



Figure 11: Underlay half with bonding agent applied on the bond interface just before pouring of overlay concrete

For the last test case that involved the use of shear studs embedded in both halves and crossing through the interface, *Tapcon* concrete screw anchors of 6 in. length and ½ in. diameter were

used (Figure 12). Four anchors were used for each specimen for both the Double-L tests and the Split-Prism tests. The embedment of these anchors in the underlay and the overlay halves of the specimens were kept identical. Holes with diameter slightly larger than the anchor diameter were drilled in the underlay bond panel with the anchors subsequently inserted horizontally, running 3 in. on either side of the panel as shown in Figure 12.



Figure 12: Tapcon anchors inserted in the bond panel

The formwork for the underlay halves for this test case were then assembled and the concrete for the underlay half was subsequently poured in the formwork. It was then placed in the oven for the 18-hour steam curing, as done for the other cases, after which the sample was demolded.

3.4.2 Overlay Samples

The preparation of formwork for the overlay halves of the specimens was comparatively easier, as standard cuboidal shapes were required to be assembled. For the L-shaped specimens, a cuboid of size (5 in. x 10 in. x 20 in.) was prepared and the cast underlay half was placed in the cuboid. The reinforcement cage was placed appropriately, and a Styrofoam block of size 5 in. x 5 in. x 1 in. was placed. The Styrofoam blocks acted as the partition at the two faces perpendicular to the bond surface between the two pours. For the test case that employed the use of shear studs, three inches of anchors protrude out from the bond surface (Figure 13). Next, the reinforcement cage was placed and finally the overlay concrete was poured over the underlay half filling the cuboid. (Figure 14). The sample was then placed in the curing room for 28 days of curing and subsequently demolded to get the composite specimen (Figure 15).



Figure 13: Underlay half with anchors protruding from the bond surface prior to pouring of overlay concrete



Figure 14: Composite specimen with freshly poured overlay concrete



Figure 15: Composite specimen for the Double-L test after demolding

Similarly, the split prism underlay half was placed in a 6 in. cube and the overlay concrete poured on top to get a composite specimen (Figure 16). This sample was then cured for 28 days in the curing room.



Figure 16: Composite specimen for the Split-Prism test after demolding

3.4.3 Curing conditions

The steam-curing process followed was consistent with the suggested practices encountered in the literature review.

After pouring the underlay concrete in the formwork, a lag period of three hours elapsed before placing the specimens in the oven (Figure 18). The initial temperature of the oven was set at 86°F (30°C) and increased to a final temperature of 140°F (60° C) in one and half hours. The temperature was raised by 9°F every 15 minutes. Once the maximum temperature of 140°F was attained, it stayed at this temperature for 15 hours following which it was again brought down to 86°F at the same rate in one and half hours. The specimens were placed in the oven for a total duration of 18 hours. Figure 17 depicts graphically the steam curing process followed. After the steam-curing, the formwork was demolded, and the samples were cooled for two hours to reach ambient temperature. The overlay concrete was poured after the samples had cooled. The 4 in. x 8 in. cylinders, cast in conjunction with the above specimens, were tested using the standard compression testing apparatus to record the average compressive strengths for the two batches.

The lag period, also known as the pre-set time, is an important factor controlling the strength development while the sample is steam-cured. For the initial trials, different values of pre-set time with three cylinders for each were tested to arrive at the optimum value for use during the actual experiments. Based on these trials, the pre-set time of three hours was found to be optimal and followed for all remaining tests. The results of these initial trials are listed in Table 7 below.

Table 7: Compressive strength of 4 in. x 8 in. cylinders for different preset times before steam curing

Compressive Strength of 4 in. x 8 in. cylinders (psi)	Preset time (hours)		
	0	1.5	3
Cylinder 1	3480.0	4326.0	6500.1
Cylinder 2	3326.8	4112.0	6080.5
Cylinder 3	3841.0	4203.0	6237.0
Average	3549.3	4213.7	6272.5

The average compressive strength for the three cylinders for this pre-set time (6272.5 psi) was also consistent with the MDOT SHA recommendation of 4500 psi minimum compressive strength for the underlay mix.

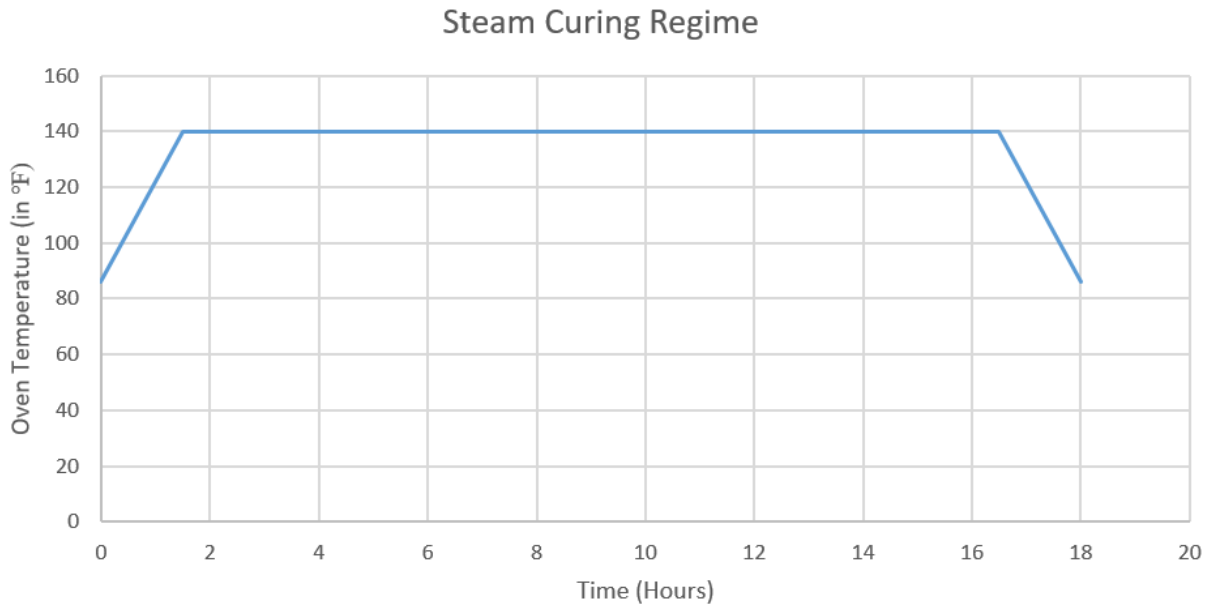


Figure 17: Steam Curing Regime for the underlay specimens



Figure 18: Underlay specimens placed in oven for steam-curing

After the underlay half was steam-cured, the overlay concrete was poured over it to get a composite concrete specimen for both Double-L and Split-Prism test specimens. The cast samples were placed for normal curing for a period of 28 days following which the samples were tested.

3.5 Test Procedures

3.5.1 Compressive Strength

The standard 4 in. x 8 in. cylinders were cast for each design mix in conjunction with the Double-L and the Split-Prism specimens.

For the underlay halves, the cylinders were placed in the oven for 18-hour steam curing and then tested for their compressive strength using the standard compression-testing machine at the lab. Three cylinders were cast for each mix for use in the compression tests.

For the overlay halves, four cylinders were cast for each mix and cured for a period of 28 days. One of the cylinders was tested after 14 days and the remaining three were tested after 28 days.

3.5.2 Shear Bond Strength

The shear strength of the bond was evaluated using the Double-L test. The composite arrangement was placed in the standard compression testing machine as can be seen in Figure 19 below. Attempts were made to ensure that the centroid of the applied load was in line with the bond interface for zero or minimal eccentricity. This was to ensure that a state of pure shear along the bond interface so that the failure load reflected the actual shear strength for the 8 in. x 5 in. bond interface. The load was applied using a standard rate of 30 ± 5 lb./s (Zia et al. 1993).



Figure 19: Testing of composite specimen for the Double-L test (Shear Bond Strength)

3.5.3 Tensile Bond Strength

The tensile bond strength was evaluated using the split-prism arrangement as shown in Figure 20. The composite cube specimen was placed such that the applied load was in line with the bond interface. The grooves were perpendicular to the direction of load. On reaching the load value for the tensile bond failure, the cube split in its two halves (underlay and overlay). This failure load (in pounds) is divided by the bond area (equal to 36 sq. in.) to get the tensile bond strength (in psi). The load rate is maintained at 30 ± 5 lb./s.



Figure 20: Testing of composite specimen for the Split-Prism test (Tensile Bond Strength)

4 Results and Discussion

4.1 Tests for Shear Bond Strength (Double-L test)

In this research work, surface roughness, use of a commercial bonding agent at the bond interface, and use of shear studs across the interface were the different test parameters. In all, seven (7) different cases were tested. The seven test cases are summarized in Table 8 below along with the number of samples cast for each test condition.

Table 8: Description of test cases and specimen count

Test case No.	Description of test case (Surface roughness condition)	No. of specimens prepared		
		L-shaped underlay and overlay halves	4 in. x 8 in. cylinders (Underlay)	4 in. x 8 in. cylinders (Overlay)
1	¼ in. x ¼ in. square grooves at 1 in. center to center spacing	4	3	4
2	¼ in. x ¼ in. square grooves at ¾ in. center to center spacing	4	3	4
3	⅜ in. x ⅜ in. square grooves at 1 in. center to center spacing	4	3	4
4	½ in. x ½ in. square grooves at 1 in. center to center spacing	4	3	4
*5	¼ in. x ¼ in. square grooves at 1 in. center to center spacing + Slurry Mix (Reference case)	4	3	4
6	¼ in. x ¼ in. square grooves at 1 in. center to center spacing + Bonding Agent	4	3	4
7	¼ in. x ¼ in. square grooves at 1 in. center to center spacing + four 6 in. long, ½ in. diameter shear studs	4	3	4

* As per the current practice of MDOT SHA, the underlying slab unit was raked to an amplitude of ¼ in. to provide a rough finish for the substrate over which the overlay concrete was poured. In this study, ¼ in. x ¼ in. square grooves were provided instead of providing the ¼ in. rake to ensure uniformity across all test specimens. In the preliminary experiments, it was observed that specimens with a simple rake without the grooves had very poor bond characteristics. Secondly, an equivalent surface roughness condition could not be replicated across all specimens with the

manual raking. For these reasons, the research team decided to proceed with ¼ in. x ¼ square grooves at 1 in. spacing as the standard roughness condition for the reference case. Moreover, the square grooves provided a better interlocking effect than a simple rake. the bond strength values reported for the reference case in this report were expected to be much higher than the ones that would have been obtained from a simple rake.

In the subsequent sections of this report, the test parameter numbers, as indicated in Table 8, will be used as references for the corresponding test cases.

4.1.1 Compressive Strength Test Results of 4 in. x 8 in. cylinders

As discussed before, three 4 in. x 8 in. cylinders were cast in conjunction with the underlay halves of the specimens for each of the seven test cases. Similarly, four 4 in. x 8 in. cylinders were cast in conjunction with the overlay halves. The readings for the tests are reported in Tables 9 and 10 for the seven test cases.

Table 9: Compressive strength test results of 4 in. x 8 in. cylinders for the underlay mix

Compressive Strength of 4 in. x 8 in. cylinders cast for the underlay mix (psi)								
Test Case No.		1	2	3	4	5	6	7
Compressive Strength after 18 hours steam-curing (psi)	Cylinder 1	7616.4	8847.0	8064.0	7723.0	8993.0	8055.0	8468.0
	Cylinder 2	6823.8	8340.1	7352.0	8987.5	8643.3	7382.0	8483.6
	Cylinder 3	8293.5	8959.0	8468.0	8740.0	8540.0	8195.0	8293.2
Average Compressive Strength after 18 hours steam-curing for the three cylinders (psi)		7577.9	8715.4	7961.3	8483.5	8725.4	7877.3	8414.9
Standard Deviation for the compressive strength for the three cylinders (psi)		735.6	329.8	565.0	670.1	237.4	434.6	105.7

Table 10: Compressive strength test results of 4 in. x 8 in. cylinders for the overlay mix

Compressive Strength of 4 in. x 8 in. cylinders cast for the overlay mix (psi)								
Test Case No.		1	2	3	4	5	6	7
Compressive Strength after 14 days of normal curing for Cylinder 1 (psi)	Cylinder 1	5670.0	5156.0	5284.7	5259.3	5229.0	5120.0	6027.5
Compressive Strength after 28 days of normal curing for Cylinders 2, 3 & 4 (psi)	Cylinder 2	6457.0	5693.5	5170.9	5426.0	5196.8	5378.0	6582.7
	Cylinder 3	5442.2	5662.0	5255.3	5291.0	5847.0	5946.0	6178.7
	Cylinder 4	5785.0	5953.0	4816.5	5612.8	5623.0	5549.0	6358.3
Average compressive strength after 28 days of normal curing for cylinders 2, 3 & 4 (psi)		5894.7	5769.5	5080.9	5443.3	5555.6	5624.3	6373.2
Standard Deviation for the compressive strength for cylinders 2, 3 & 4 (psi)		516.2	159.7	232.8	161.6	330.3	291.4	202.4

4.1.2 Results for the Shear Bond Strength Test

Table 11 shows results for shear bond strength for the seven test cases. Figure 21 is a plot of average shear bond strength for the seven test cases and Figure 22 shows the Double-L specimens after the shear bond failure.

Table 11: Results for shear bond strengths (Double-L Test)

Shear bond strengths using the Double-L Test (psi)								
Test Case No.		1	2	3	4	5	6	7
Shear bond strength after 14 days of normal curing for Specimen 1 (psi)	Specimen 1	730.3	497.5	538.5	654.5	365.0	180.8	1355.7
Shear bond strength after 28 days of normal curing for Specimens 2, 3 & 4 (psi)	Specimen 2	560.3	743.3	653.3	639.0	562.0	260.5	1398.3
	Specimen 3	549.0	558.5	671.3	642.0	380.0	285.5	1438.8
	Specimen 4	721.3	380.0	646.3	405.0	680.0	320.0	1321.5
Average shear bond strength after 28 days of normal curing for Specimens 2, 3 & 4 (psi)		610.2	560.6	657.0	562.0	540.7	288.7	1386.2
Standard Deviation for the shear bond strength for Specimens 2, 3 & 4 (psi)		96.4	181.6	12.9	136.0	151.1	29.9	59.6

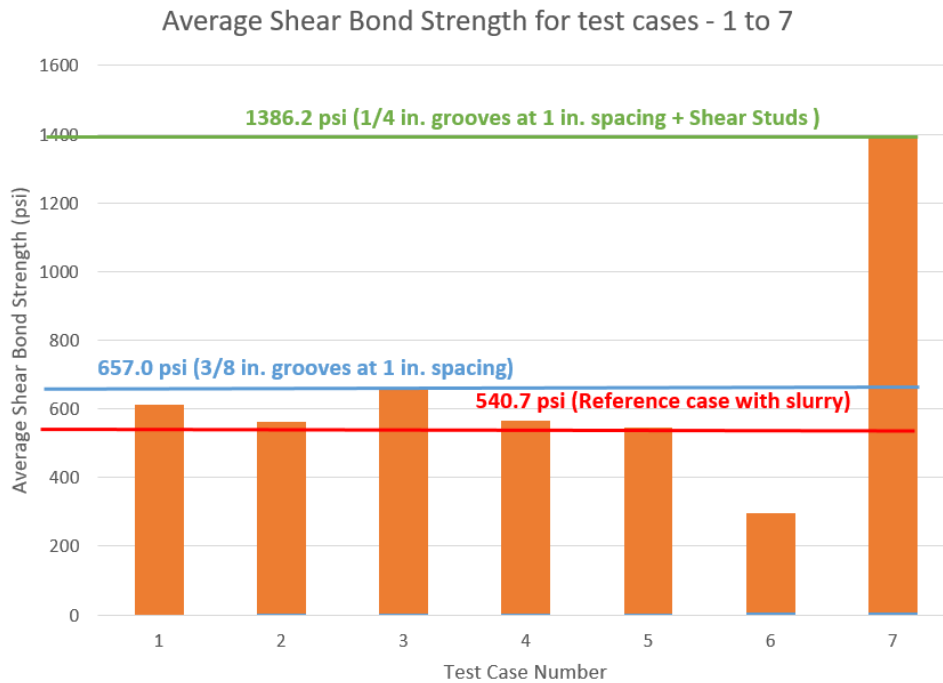


Figure 21: Comparison chart for the average shear bond strength for the seven test cases



Figure 22: Composite specimen after shear bond failure in the Double-L test

4.2 Tests for Tensile Bond Strength (Split-Prism Test)

The tensile bond strength was tested by a Split-Prism test. The composite specimens for these tests were 6 in. cubes comprising of two halves of 3 in. x 6 in. x 6 in. cuboids. The only exception was the specimen size used for the test case involving use of shear studs. For the test case, 8 in. cubes comprising of two halves of 4 in. x 8 in. x 8 in. cuboids were prepared with shear studs, having the required 3 inches of penetration, across both halves. The load was applied in a manner such that it was in line with the bond interface with the grooves perpendicular to the load direction to prevent eccentric loading.

Similar procedures were followed while preparing the underlay and the overlay specimens for the split-prism tests as indicated previously for the shear strength tests. Identical materials for the mix, mix specifications, groove configurations, etc. were employed for these tests as well. Also, three 4 in. x 8 in. cylinders were cast for each underlay mix and four 4 in. x 8 in. cylinders were cast for each overlay mix. One of the four composite specimens was tested after 14 days of curing and the remaining three were tested after 28 days of curing.

4.2.1 Compressive Strength Results of 4 in. x 8 in. cylinders

Three 4 in. x 8 in. cylinders were cast for each of the seven test cases for the underlay mix and four 4 in. x 8 in. cylinders were cast for each test case for the overlay mix. The readings for the tests are reported in Tables 12 and 13.

Table 12: Compressive strength results of 4 in. x 8 in. cylinders for the underlay mix

Compressive Strength of 4 in. x 8 in. cylinders cast for the underlay mix (psi)								
Test Case No.		1	2	3	4	5	6	7
Compressive Strength after 18 hours steam-curing (psi)	Cylinder 1	8923.0	7637.1	8222.0	7198.0	8317.4	8165.0	8438.0
	Cylinder 2	8180.0	7542.0	8428.0	7679.0	8112.7	8442.0	8143.4
	Cylinder 3	8245.0	7893.0	8388.0	8102.6	8644.0	7467.0	8180.0
Average Compressive Strength after 18 hours steam-curing for the three cylinders (psi)		8449.3	7690.7	8346.0	7659.9	8358.0	8024.7	8253.8
Standard Deviation for the compressive strength for the three cylinders (psi)		411.5	181.5	109.2	452.6	268.0	502.4	160.6

Table 13: Compressive strength results of 4 in. x 8 in. cylinders for the overlay mix

Compressive Strength of 4 in. x 8 in. cylinders cast for the overlay mix (psi)								
Test Case No.		1	2	3	4	5	6	7
Compressive Strength after 14 days of normal curing for Cylinder 1 (psi)	Cylinder 1	6102.0	5578.0	4565.4	5198.0	6861.2	5974.0	6085.4
Compressive Strength after 28 days of normal curing for Cylinders 2, 3 & 4 (psi)	Cylinder 2	6226.6	5827.1	4843.0	5420.3	6992.0	5389.0	6978.7
	Cylinder 3	6493.0	5743.0	5573.6	5229.0	7043.0	6182.0	6527.0
	Cylinder 4	6217.6	6008.1	5403.3	5512.0	7127.0	5684.0	6778.2
Average compressive strength after 28 days of normal curing for cylinders 2, 3 & 4 (psi)		6312.4	5859.4	5273.3	5387.1	7054.0	5751.7	6761.3
Standard Deviation for the compressive strength for cylinders 2, 3 & 4 (psi)		156.5	135.5	382.2	144.4	68.2	400.8	226.3

4.2.2 Results for the Tensile Bond Test

As performed for the shear bond tests, four 6 in. composite cubes were cast for test cases 1 to 6 and four 8 in. composite cubes were cast for test case number 7 involving the use of shear studs. The load value, when the composite sample splits into its two constituent halves, was recorded and divided by the interface area to get the split tensile strength results.

Table 14 shows results for tensile bond strength for the seven test cases. Figure 23 is a plot of tensile bond strength for the seven test cases and Figure 24 shows the split-prism specimens after the tensile bond failure.

Table 14: Results for tensile bond strengths (Split-Prism Test)

Tensile bond strengths using the Split-Prism Test (psi)								
Test Case No.		1	2	3	4	5	6	7
Tensile bond strength after 14 days of normal curing for Specimen 1 (psi)	Specimen 1	520.0	471.4	436.7	277.2	630.0	542.8	876.7
Tensile bond strength after 28 days of normal curing for Specimens 2, 3 & 4 (psi)	Specimen 2	529.3	583.5	553.3	684.7	722.5	504.0	829.4
	Specimen 3	485.0	658.9	455.8	486.7	604.7	420.3	922.7
	Specimen 4	228.0	590.5	526.9	298.3	767.2	573.9	984.4
Average tensile bond strength after 28 days of normal curing for Specimens 2, 3 & 4 (psi)		414.1	611.0	512.0	489.9	698.1	499.4	912.2
Standard Deviation for the tensile bond strength for Specimens 2, 3 & 4 (psi)		162.7	41.7	50.4	193.2	83.9	76.9	78.0

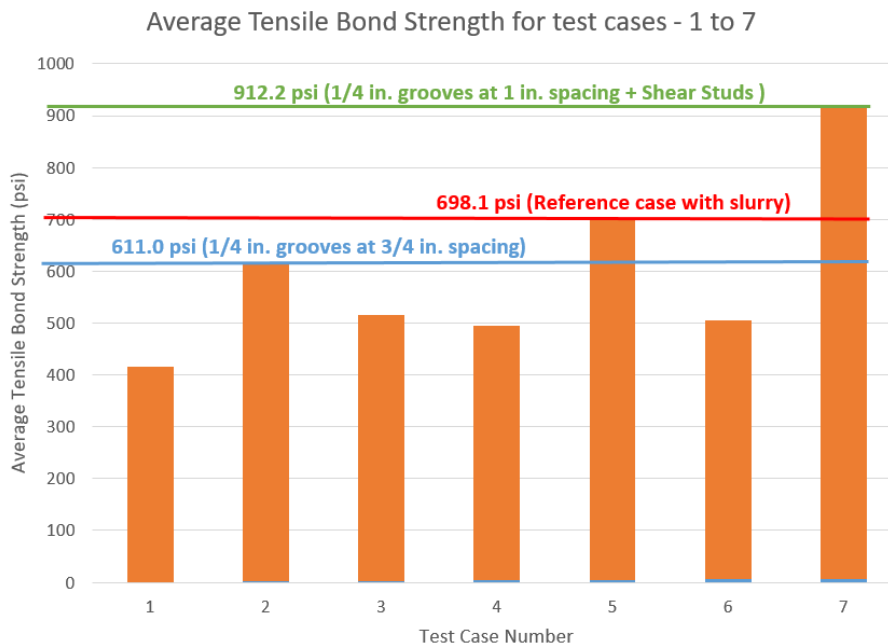


Figure 23: Comparison chart for the average tensile bond strength for the seven test cases



Figure 24: Composite specimen after tensile bond failure in the Split-Prism test

4.3 Discussion of test results

From the test results, it was observed that test case number 5, that used the cement-sand slurry mix at the bond interface in addition to the $\frac{1}{4}$ in. grooves at 1 in. spacing, reached the minimum shear bond strength value of all test cases, except test case number 6 that uses *Eneclad Superbond* bonding agent. For both cases (test case numbers 5 and 6), the use of slurry and commercial bonding agent formed a potentially weak layer at the interface. In both cases, that weak layer lead to early failure when compared against the other five test cases. It was also noted that in this study, the reference test case has $\frac{1}{4}$ in. square grooves spaced at 1 in. on the underlay substrate instead of the $\frac{1}{4}$ in. rake pattern that MDOT SHA provides in their current projects. The tested groove configuration provided a better interlocking effect; therefore, the bond strengths results reported are higher than the results that would have been obtained if a simple rake was to be provided instead.

The key outcome from this study was the improved shear strength characteristics for the bond when square grooves were introduced along the interface. The grooves, in addition to, good surface preparation procedures help develop a good interlocking effect and improve the performance of the overlay bond in shear. For the tensile strength tests, the values for the test cases with grooves are lower than the reference case but are still higher than recommended values by Virginia DOT (233 psi) (Sprinkel 1993), Oklahoma & New Mexico DOT's (250 psi), and Oregon DOT (175 psi) (Appendix A). In field tests using ACI 503R tensile adhesion tests (Pull-off tests) on fourteen bridge decks with latex-modified concrete (LMC) overlays by the Virginia DOT, the average tensile rupture strength for LMC overlays was 233.0 psi. It was reported that the tensile rupture strength at the bond interface between the overlays and the

substrate provided for a good bond that could be maintained for a period of 20 years or more. Igwe et al. (2016) conducted laboratory tests to study correlation between tensile strength values obtained using Split Cylinder tests and Double Punch test (Pull-off test). The average tensile strengths for rubberized asphalt concrete mixtures recorded using Split Cylinder tests were around 15 % higher than the strength values obtained using Double Punch test.

In this research study, splitting tensile strength of the prisms were reported as tensile bond strength values. The average bond tensile strength values recorded, for test cases with only grooves on the underlay substrate, were significantly higher than the average tensile rupture strength of 233.0 psi in the field tests done on LMC overlays by VDOT. These LMC overlays provided a service life of 20 years or more and also exceeded the values recommended by Oklahoma, New Mexico and Oregon DOT's.

5 Conclusions, recommendations and future work

5.1 Conclusions

The research team, in consultation with MDOT SHA, performed an experimental study to analyze the effects of different interface conditions on the bond strength of cast-in-place reinforced concrete deck overlays on prestressed concrete slabs. MDOT SHA currently uses a cement-sand slurry mix as the bonding agent when placing cast-in-place reinforced overlays over prestressed slab bridge decks for small bridges up to 55 ft. span or multiple 55 ft. elements for longer bridges. This practice is very cumbersome, inefficient, and time-consuming as it requires removal of the reinforcement cage for the overlay from its position, quick application of the slurry mix and placement of the cage back to its position. The reinforced concrete deck overlay is poured over the substrate while the slurry is still in a non-set condition.

The research team conducted a thorough literature review on different factors that may affect the overlay bond strength such as surface roughness, the use of bonding agents and the use of mechanical devices, such as shear studs, across the interface. The research team also reviewed different test methods to quantify bond strengths as part of this study. From the literature reviewed, it was clear that surface roughness and preparation were the most important factors to achieving a good bond between the concrete overlay and the prestressed concrete slab. The research team developed seven test cases with different bond interface conditions, including a reference test case that uses the application of a slurry mix with surface roughness. Of the remaining six test cases, four involved application of different square groove configuration (surface roughness) on the substrate, one case involved use of a commercial bonding agent, *Enecon Superbond*, in addition to grooves, and the last case involved use of four – 6 in. long anchors of ½ in. diameter embedded equally in both layers (underlay and overlay) in addition to the grooves. The concrete materials used, the mix design specifications and curing processes for both the underlay and the overlay halves of the specimens were completed in accordance with current MDOT SHA specifications and industry practices. Based on the conducted literature review, two sets of tests were designed in this study to quantify the bond strengths: Double-L test and the Split-Prism test to evaluate the shear bond and tensile bond strengths, respectively. For both test layouts, efforts were made to minimize eccentric loading by ensuring that the applied load was in line with the interface. The test specimens were loaded to failure, and the recorded load values were divided by the interface areas to get the shear bond and tensile bond strength values for the corresponding test cases. In addition, compressive strength tests for each mix were conducted to ensure that the mix strengths were consistent for all test cases. The test results for all the remaining cases were compared against the results obtained for the reference test case involving application of slurry mix.

The results obtained from this study were very positive concerning possible use of prestressed precast slabs with pre-existing grooves over which the overlay concrete can be directly poured. The average shear bond strength values for the four test cases that had different square groove configurations (¼ in., ⅜ in. and ½ in. deep grooves at spacing of ½ in and 1 in.) on the underlay

substrate were recorded to be higher than the reference test case that used the slurry mix. The interlocking effect obtained through these grooves contributed significantly to the shear bond strength. For the tensile strength tests, the values for the test cases with grooves only were lower than the reference case but were still higher than recommended values by Virginia DOT (233 psi) (Sprinkel 1993), Oklahoma & New Mexico DOT's (250 psi), and Oregon DOT (175 psi) (Appendix A).

5.2 Recommendations

Based on the results obtained in this study, the research team recommends the use of prestressed precast slabs with pre-existing grooves, manufactured at plants, in future projects. As noted previously, providing a square groove configuration on the deck slab that runs transverse to the traffic direction significantly improved the shear strength of the bond between the overlay and the prestressed concrete slabs. The average shear bond strength values for all the four test cases that only have square grooves without any additives are higher than the reference case in which slurry mix was used. If the recommendations made in this report are followed, the use of slurry mix could be eliminated altogether prior to pouring of overlay concrete. The research team consulted *Northeast Prestressed Products, LLC* in Pennsylvania, one of the fabricators for MDOT SHA, and discussed the possibility of manufacturing precast slabs with grooves engraved on the surface. A plant representative informed the research team that prestressed, precast slabs with pre-existing grooves can be cast at the plants provided the mix is workable enough for a consistent flow of concrete inside the grooves. The precast panels with grooves manufactured at plants need to be thoroughly cleaned before the overlay concrete is poured. The grooves help create an interlocking effect and improve the bond. As evidenced in test case number 7, addition of shear studs helps further improve the shear bond and tensile bond but may not be practical to implement.

5.3 Future Work

The following bullets indicate proposed future areas of study for consideration:

- Applicability of different groove configurations can be tested in future research to arrive at some optimum configuration with regards to strength and economy.
- Possibility of using different commercial bonding agents can be further studied.
- Applicability of different shear stud configurations can be investigated.

6 References

1. ASTM C1583 - 04, *Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off method)*.
2. ASTM C882/C882M - 05, *Standard Test Method for Bond Strength of Epoxy Resin Systems used with Concrete by Slant Shear*.
3. Bakhsh, K.N. (2010). *Evaluation of Bond Strength between Overlay and Substrate in Concrete Repairs*. Thesis. Royal Institute of Technology, Division of Concrete Structures.
4. Bissonnette, B., Vaysburd, A. M., and Fay, K. F. von. (2012). *Best Practices for Preparing Concrete Surfaces Prior to Repairs and Overlays*.
5. Chapter 12 – Curing, University of Memphis. Retrieved from http://www.ce.memphis.edu/1101/notes/concrete/PCA_manual/Chap12.pdf. Web September 11, 2017.
6. Choi, D.U. (1996). *An Experimental Investigation of Interface Bond Strength of Concrete Using Large Powder-Driven Nails*. The University of Texas at Austin.
7. Choi, D.-U., Jirsa, J. O., and Fowler, D. W. (1999). *Shear Transfer across Interface between New and Existing Concretes Using Large Powder-Driven Nails*. ACI Structural Journal, 96(2).
8. Delatte, N. J. J., Wade, D. M., and Fowler, D. W. (2000). *Laboratory and Field Testing of Concrete Bond Development for Expedited Bonded Concrete Overlays*. ACI Materials Journal, 97(3).
9. Dural Prep AC. Euclid Chemical. Tech. Cleveland: Euclid Chemical. 2016. Print.
10. Edison Coatings Inc. Flexi-Bond 540. Tech. Connecticut: Edison Coatings Inc. 2003. Print.
11. Eneclad Superbond. Eneclad Superbond. Tech. New York: Enecon Superbond. 2015. Print.
12. Euclid Chemical. *Latex Bonding Agents for Concrete*. Technical Bulletin CP-15.
13. Evaluation of bond strength between overlay and substrate in concrete repairs (Thomas), PaveMaintenance Wikispaces. Web September 11, 2017.
14. Gurley, E. (2011), *To Cure or Not to Cure*, Precast Inc. Magazine, National Precast Concrete Association.
15. Harrington, D., DeGraaf, D., Riley, R., Rasmussen, R. O., Grove, J., and Mack, J. (2007). *Guide to Concrete Overlay Solutions*.
16. Indiana Department of Transportation. (2014). *Standard Specifications, 2014*.
17. Igwe, A., Ekwulo, O., Ottos, G. (2016). *Correlation of Tensile Strength of Split Cylinder Test and Double Punch Test of a Rubberized Asphalt Concrete Used in Flexible Pavement Design*. International Journal of Constructive Research in Civil Engineering. Volume 2, Issue 5, 2016, PP 8-15.
18. Júlio, E. N. B., Branco, F. A., and Silva, V. D. (2004). *Concrete-to-concrete bond strength. Influence of the roughness of the substrate surface*. Construction and Building Materials, 18(9), 675–681.

19. (2017) Instruments, Germann. Bond-Test ASTM C-1583. Tech. Illinois: Germann Instruments. Print.
20. Krauss, P. D., Lawler, J. S., and Steiner Wiss, K. A. (2009). *Guidelines for selection of bridge deck overlays, sealers and treatments*.
21. Lee, C., Lee, S., and Nguyen, N. (2016). *Modelling of Compressive Strength Development of High-Early-Strength-Concrete at different curing temperatures*, International Journal of Concrete Structures and Materials.
22. Mailvaganam, N.P. (1997) *Effective Use of Bonding Agents*. Institute for Research in Construction 11 n. pag. Print.
23. Maryland Department of Transportation, State Highway Administration (2018). *STANDARD SPECIFICATIONS for CONSTRUCTION and MATERIALS*.
24. Mccullough, B. F., and Fowler, D. W. (1994). *BONDED CONCRETE OVERLAY (BCO) PROJECT SELECTION, DESIGN, AND CONSTRUCTION*.
25. Mousa, M.I. (2015). *Factors Affecting Bond between Repairing Concrete and Concrete Substrate*. International Journal of Engineering and Innovative Technology 4.11.
26. Phares, B. et al. (2016), *Investigation of Techniques for accelerating the construction of bridge deck overlays, Final Report April 2016*, Bridge Engineering Center, Iowa State University.
27. Phares, B., Hosteng, T., Greimann, L., and Pakhale, A. (2016). *Investigation of Techniques for Accelerating the Construction of Bridge Deck Overlays*. Iowa State University Institute for Transportation.
28. Ramezani-pour, A.A., Khazali, M.H., and Vosoughi, P. (2013). *Effect of steam-curing cycles on strength and durability of SCC: A case study in precast concrete*, Construction and Building Materials, Volume 49.
29. Ray, I., Davalos, J. F., and Luo, S. (2005). *Interface evaluations of overlay-concrete bi-layer composites by a direct shear test method*. Cement and Concrete Composites, 27(3), 339–347.
30. Silfwerbrand, J. (1990). *IMPROVING CONCRETE BOND IN REPAIRED BRIDGE DECKS*. Concrete International, 12(9).
31. Silfwerbrand, J. (2003). *Shear Bond Strength in Repaired Concrete Structures*, Materials and Structures, Vol. 36.
32. Silfwerbrand, J., Beushausen, H., and Courard, L. (2011). *Bonded Cement-Based Material Overlays for the Repair, the Lining or the Strengthening of Slabs or Pavements*. (B. Bissonnette, L. Courard, D.W. Fowler, and J.-L. Granju, eds.). State of the Art report of the RILEM Technical Committee 193-RLS.
33. Sprinkel, M. (1993). *Twenty-year performance of latex modified concrete overlays*.
34. Trevino, M., McCullough, B. F., and Fowler, D. W. (2003). *Techniques and Procedures for Bonded Concrete Overlays*.
35. Wade, D. M., Fowler, D. W., and Mccullough, B. F. (1995). *CONCRETE BOND CHARACTERISTICS FOR A BONDED CONCRETE OVERLAY ON IH-10 IN EL PASO*.
36. Zia, Paul et al. (1993), *Mechanical Behavior of High Performance Concrete, Volume I*, Strategic Highway Research Program.

Appendix A

Survey Responses from different state DOTs

As part of the literature review, the authors, in consultation with Mr. Jeff Robert and Ms. Sharon Hawkins from MDOT SHA, prepared a questionnaire that was sent to all state DOT's. The responses received from the questionnaire were helpful in designing the experiment, the selection of appropriate groove configurations for the test cases, and so on. An overview of the responses received are documented in this section.

The purpose of this survey was to identify the current practices used by other state DOTs to ensure good adhesion between the concrete overlay and the prestressed concrete slabs, and any test methods that may have been adopted to test the bond strength of concrete overlays.

Of the survey respondents, the state DOTs not using an overlay on bridge decks and/or prestressed slabs are Alaska, Florida, Louisiana, Mississippi, Oklahoma and South Dakota.

Roughening the surface profile on top of prestressed slabs was a common practice stated from Delaware, Indiana, New Hampshire, Tennessee, Texas, Vermont and West Virginia state DOTs. The roughening was per the AASHTO specifications, except in Indiana, which uses hydro-demolition techniques to prepare the prestressed slab surface before the overlay is placed. In some cases, like West Virginia, the DOT instructs the box beam fabricators to roughen the surface of the box beam.

Q. What are the current standards and specifications used in your agency for ensuring a good bond between concrete overlay and prestressed concrete slabs when constructing concrete overlays over prestressed slabs for new bridges?

It was noted that the current standards for many states recommend treatment of substrate surface prior to the overlay placement to ensure good bond strength for the interface. Delaware recommends texturing the top surfaces of beams. The DOTs in Tennessee, Vermont and West Virginia recommend that the top surface of the substrate be roughened to get surface profiles that facilitate better integration of this layer with the overlay.

Q. If your DOT uses mechanical methods such as shear studs or reinforcement from the slabs to connect the precast slabs to the concrete overlay, has your agency developed a specification and/or any testing methods?

Out of responses received, Vermont, Rhode Island and West Virginia used reinforcement across the interface of overlay and substrate to improve the bond characteristics. The Vermont DOT recommends the use of a mild reinforcement extended from beam into deck. The West Virginia DOT uses reinforcement bars bent in an M shape protruding from the box beam. As for the other respondents, there was no indication of the use any such mechanical method(s) to connect the deck slab to the concrete overlay.

Q. If you use commercial adhesives as bonding agent, can you provide name(s) of the vendors your DOT uses?

None of the states, except for New Mexico, used or indicated any preference for specific bonding agents. The New Mexico DOT recommended the use of *WR Meadows, Inc.*'s *Acry-lok* as a bonding agent.

Q. What is/are the recommended test(s) used in your department for testing tensile and shear strength of the bond in concrete overlays?

Most of the state DOTs indicated no standard tests for tensile and shear strength of the bond in concrete overlays in their responses. Listed below are the state DOTs which indicated specific test methods:

Iowa: Recently conducted research on techniques for accelerating the construction of bridge deck overlays (Phares, Brent et. al 2016). One of the components of that research work included four different laboratory tests (pull-off tests, push-out tests, flexural test with positive bending and flexural tests with negative bending) to study overlay bond performance.

Oklahoma: Performed tensile strength tests in accordance with ASTM C 1583. The tensile strength must have a minimum strength of 250 psi with 100 percent of the failure taking place in the existing concrete deck.

New Mexico: Performed adhesion tests according to ACI 503R - Appendix A of the American Concrete Institute (ACI) Manual of Concrete Practice. The test shall obtain a 250-psi minimum pull-off or cohesive failure within existing concrete.

Oregon: Performed two bond tests for each placement in the presence of and at locations designated by the Engineer within 28 calendar days of overlay placement and before opening the roadway to traffic. The test primarily consists of drilling a core through the overlay and subsequently exerting a tensile load to the core up to failure or 300 psi, whichever occurs first. A successful test is the failure of the concrete substrate or bond failure at/or above 175 psi.

Texas: Performed the Slant Shear Bond Test.

Colorado: Performed the Sounding Test per ASTM D4580.