ABSTRACT

Title of Thesis:	INFLUENCE OF USING BONDING AGENT AND SHEAR STUDS ON BOND STRENGTH OF CONCRETE OVERLAYS ON PRESTRESSED SLABS
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This study explores the effects of using bonding agent and shear studs in conjunction with a defined surface roughness condition on the bond strength of concrete overlays poured over prestressed concrete slabs. The shear bond and tensile bond strengths are tested for seven cases by using Double-L test and Split-Prism test respectively. The test variables are surface roughness, use of slurry mix, commercial bonding agent and shear studs at the interface. Application of grooves on the substrate provides a good bond owing to an interlocking effect. Application of bonding agent results in the lowest bond strengths by introduction of a plane of weakness. The bond strength values where shear studs are used are the highest of all test cases. Based on the findings from this study, a recommendation is made to Maryland Department of Transportation to use precast panels with pre-existing grooves and simply pour the overlay concrete on top.

INFLUENCE OF USING BONDING AGENT AND SHEAR STUDS ON BOND
STRENGTH OF CONCRETE OVERLAYS ON PRESTRESSED SLABS

by

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1 Introduction

1.1 Background

Pre-stressed concrete bridges are subjected to heavy loads from moving vehicles over their life. They are also prone to harsh environmental conditions that adversely affect their service life. Thus, it is imperative that timely repair and rehabilitation of these bridges should be carried out; this is a costly affair in terms of the materials used and the economic losses attached with disruption in moving traffic during the duration of the repair.

Use of concrete overlays is very common in repair of pre-stressed concrete bridge decks. They aid in extending the service life of these bridges in that they provide a durable, improved frictional riding surface and help in increasing the load carrying capacity of the deck. They also act as an effective barrier to deicing salt and prevent the corrosion of reinforcement in the underlying bridge deck due to these salts. These concrete overlays are very commonly used by different state Department of Transportations (DOTs). They are used for repair and rehabilitation of existing bridges as well as on newly constructed bridge decks.

Different types of concrete overlays are used for repair of bridge 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.

Bond strength of the interface between the overlay and the bridge deck is the most important consideration for adequacy of these overlays. Due to the heavy traffic on these bridges, the interface is subjected to heavy shear forces at the interface, causing strain in the bond. It is

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imperative that the bond strength should be adequate to ensure that the desired service life for both the overlays and the bridge deck are achieved.

Currently, different state DOTs use various methods to provide good bond characteristics between the concrete overlay and the bridge decks. The methods involve use of Portland cement grout, latex modified cement grout, cement slurry, use of bonding agents and mechanical devices embedded in both surfaces through the interface such as mechanical shear studs.

The use of bonding agents poses a significant challenge during construction, as their application is time-sensitive. It requires the contractor to remove the reinforcement of the overlay after they have been laid out and cut, thoroughly clean the underlying concrete, applying the bonding agent, and quickly replace the reinforcement and cast the slab before the bonding agent sets or dries.

Aside the difficulty and time consuming nature of using bonding agents, there is some evidence in the literature that question their usefulness in concrete overlays when proper surface preparation and placement procedures are followed. Bonding agents such as grouts and slurries have higher water-cement ratios, and thus are more permeable. They may introduce a plane of weakness, and can result in lower bond strengths than when no bonding agents are used. Some researchers believe 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, few methods such as shear test using two L-shaped specimens, and tensile tests such as the Pull-out test, Split-prism test are considered acceptable based on the literature review conducted for this study.

In most studies done so far on bond strength characteristics of concrete overlays, different surface roughness techniques have been employed to enhance the bond strength and are then evaluated using the standard tests available. In this research work, effect of use of a commercial bonding agent on the underlying slab and use of mechanical shear studs on the bond characteristics of the concrete overlay are studied. The bonding agent and the shear studs are used in conjunction with a standard groove configuration running along the underlay surface. It is to be noted that the above two cases are in addition to four other cases that only employ use of

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different groove configurations without any additives (two groove sizes and two different spacing distances between adjacent grooves) to enhance the overlay bond strength. The last test case is the reference test case that involves application of slurry mix over the underlay surface prior to application of the overlay concrete.

1.2 Research Approach

Currently, the Maryland Department of Transportation, State Highway Administration (MDOT SHA) uses the slurry mix for the overlay on prestressed slabs. This is a tedious process in that the reinforcement cage for the overlay needs to be lifted prior to application of slurry, then the slurry is poured and then the cage required to be put in place immediately so that the slurry is still wet and then finally the overlay concrete is poured.

This research project intends to come up with a different method for improving bond strength that is more convenient, at the same time cost effective. Primarily, the project involves use of concrete specimens to simulate the behavior of concrete overlay and bridge deck bond and then test the bond strength for the specimens. The first area of interest of this study is on the effect of using a commercial bonding agent selected after careful review of available products in the market. Secondly, the effect of shear studs with equal embedment across both interfaces on the overlay bond strength is studied. For both of these cases, the additives – bonding agent and shear studs supplement the effects of a standard groove configuration running along the underlay surface on the overlay bond strength. The results for the bond strength for these cases are compared against the reference case involving use of slurry mix to make meaningful inferences from the test results.

In this project, two different test types are used – Double L test for the shear strength and split-prism test for the tensile strength. For both tests, two identical halves for the respective tests are prepared – 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 cured for a period of 28 days under standard curing conditions and finally tested using the standard compression testing machine apparatus at the National Ready Mix Concrete Association (NRMCA) laboratory.

For the specimens, four different groove configurations were selected for use in test; the configurations were arrived on basis of the literature review and responses received from different state DOTs from the survey conducted. The configurations were – ¼ in. groove size at

1 in. spacing, ¼ in. groove size at ½ in. spacing, 3/8 in. groove size at 1 in. spacing and ½ in. groove size at 1 in. spacing.

The concrete specimens were prepared with the intention of simulating the behavior of the actual overlay bond as closely as possible. Thus, the first halves were prepared using Type-III cement and subjected to 18 hours of steam curing to achieve high early strength. The steam curing regime selected for the underlay specimens is consistent with the practice being followed by the plants manufacturing the precast slabs. The second halves that represented the concrete overlay were prepared using Type-I cement and the composite specimen was then subjected to 28 days of normal curing under standard conditions.

1.3 Objectives and Scope of this Study

The current practice adopted by MDOT SHA is to use cement-sand slurry mix as an additive on the underlying prestressed slabs.

As per the current practice being followed by MDOT SHA, the reinforcement cage of the overlay slab should be placed in a manner that allows it to be lifted on and off the underlying slab before pouring the overlay concrete. The cage should be restrained by temporary supports such as diagonal reinforcement bars, or steel angles so that its configuration is not disturbed while it is being lifted on and off. It should be ensured that the reinforcement is properly laid after levelling up the surface. The reinforcement cage is lifted up just prior to the placement of overlay concrete and the deck is cleaned thoroughly.

The underlying slab surface is to be cleaned thoroughly and subjected to abrasive blasting to clear it of any dust particles. The substrate is cleaned thoroughly and subjected to abrasive blasting no more than 24 hours before overlay concrete placement. This is followed by cleaning the substrate surface by air blasting and subsequent water flushing. In addition, the surface is kept wet for a period of one hour before laying the overlay concrete. The surface is wetted for a minimum period of one hour before laying the overlay concrete 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(s).

It is very important that the slurry be kept in a fluid state while the overlay concrete is being poured. To achieve that, misting operations are used very frequently at the job sites.

As evident from the preceding paragraphs, the current practice followed by MDOT SHA for placing overlay concrete on prestressed slabs is very tedious, cumbersome and requires great attention from the workers at the job site. This study intends to address the above concerns by suggesting other possible alternative procedures that allow for a seamless construction while providing adequate strength for the overlay bond. In this experimental study, the research team performed the following tasks:

- Surveyed current practices used by other State DOTs in regards to bonding concrete overlays, specifications, published literature on field performance, testing methods, etc.
- Investigated bond strength and performance of overlays that utilize slurry mix, no slurry mix, commercial bonding agent 'Eneclad Superbond', and anchors of 6 in. length and ½ in. diameter with equal embedment across both layers.
- Compared the bond strength and performance of the test cases involving use of groove configurations along the substrate surface, bonding agent, shear studs and the reference case involving use of a cement-sand slurry mix as the bonding agent.
- Developed specifications and best practices for pouring the overlay concrete on prestressed slabs to be employed in future projects of MDOT SHA.

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. In order for bonded concrete overlays to serve their purpose, they have to be able to provide a strong bond between the two concrete layers in order to prevent delamination or debonding.

A complete bond between the prestressed planks and the overlay is critical in order to achieve monolithic action. Bond strength is usually defined as tensile strength perpendicular to the interface plane. However, bond strength in shear may also be considered given its inherent role and intrinsic relationship with tensile behavior (Silfwerbrand 2003; Silfwerbrand et al. 2011). 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 just cement slurry as it reduces the cement and water content, which could lead to shrinkage cracks. Grouts also have similar issues with high cement and water demand. Excessive water in the grout will lead to weak bonds. Cement slurries containing non-re-emulsifiable latex emulsions can also be used as bonding 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 should be given to their formulation as they directly affect their performance. In general, primers or bond coats are usually not needed for overlays involving Portland cement concrete, as the paste fraction of the concrete makes a good bonding agent between the overlay (Krauss et al. 2009). In this study, commercial bonding agent *Eneclad Superbond* is selected for one of the test cases to gauge its

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impact on the bond strength of the overlay. This product is chosen after thorough review of literature for applicability of bonding agents and three other similar products as mentioned in a later section of this document.

Mechanical crossing devices such as nails and stirrups have been used to strengthen bond strength of concrete overlays. 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). However, stirrups do not work until bond has broken, because they have to be strained before they can carry any significant load. For this study, in consultation with MDOT SHA, the research team prepared a questionnaire for a survey sent to all the state Department of Transportations (DOTs) to get an idea about their current practices. Missouri Department of Transportation uses L-shaped reinforcement as mechanical crossing devices for concrete overlays on prestressed slabs in bridges. West Virginia DOT uses reinforcement bars bent in M shape protruding from the box beam as mechanical devices to improve the bond characteristics.

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

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 worked out 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 dry substrate surface prior to overlay placement works out best for achieving good bond strengths. It is recommended that the substrate surface be cleaned twice - first time immediately after water jetting and the other just before laying the overlay concrete.

Talbot et al. investigated the influence of different interface textures and concluded that smooth surfaces 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 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. Swedish National Road Administration recommends the use of vibration pokers and vibration platforms to achieve proper compaction. Self-consolidating materials (with high workability) are expected to lead to higher effective contact area and then to higher bond strength. Properties of the hardened overlay material also influence the bond properties. It is observed is some studies that both - tensile and shear bond strength are proportional to the early age concrete strength. Excessively impermeable overlays result in stresses 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 $4°$ C) results in a lower initial bond strength but higher long-term bond strength in comparison to substrates at higher temperatures ($21°$ C or $38°$ C).

Use of grouting material (such as cement slurry used in the current practice by MDOT SHA) is also a good practice to ensure good bonding at the interface. They improve bond strength for certain overlay materials; they are highly recommended when applying stiff repair mortars on the substrate surfaces to properly fill the pores and cavities found on the substrate surface.

Once the overlay concrete is laid out on the substrate surface, it should be subjected to a minimum of five days of water curing for proper strength development. During the curing regime, exposure to direct sunlight was found to have a detrimental effect on the shear bond strength.

Once the overlay concrete is placed, continuous and limited vibrations due to moving traffic may increase both overlay strength and bond strength. However, heavy vibrations starting a few hours after overlay placement should be avoided. Manning stated that the best way of preventing heavy vibrations is to maintain a smooth riding surface and a smooth transition at the expansion joints of the bridge.

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, and mechanical crossing devices.

Of all the factors that influence bond strength, surface preparation and cleaning of the substrate concrete is the most important. Common surface preparation methods used in rehabilitation of bridge decks include mechanical roughing and blast methods using abrasives, high-pressure water, or a mixture (Bissonnette et al. 2012). In the following sections, different factors that affect the bond strength at the interface are discussed in detail. Different options that improve the bond characteristics would be considered and possibility of incorporating the desired surface conditions into the planks would be consulted with the prestressed plank manufacturers.

2.3.1 Bond surface conditions

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

2.3.2 Slurry/Overlay bonding grout

The slurry specifications are according to MDOT SHA manual SHA 440.02.05. To prepare the slurry, equal parts by weight of portland cement and sand are mixed with sufficient water. It is to be ensured that the consistency of the mix allows for application of the mix with a stiff brush or broom in a thin, even coating that will not run or puddle. 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 the overlay on top of it.

2.3.4 Use of shear studs

As discussed in a preceding section, mechanical crossing devices such as shear studs serve to improve the bond characteristics of concrete overlays. The additional strength developed by providing shear studs supplements the bond strength from the concrete. Therefore, use of these studs provides for an additional strength margin for bonded concrete overlays on the underlying slab. Missouri Department of Transportation 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 research study, for one test case, mechanical bond between both interfaces is developed by employing use of *Tapcon* bars of 1/2 in. diameter and 6 in. length – with embedment of 3 in. in both the underlay and the overlay half. The specifications and layout of the shear studs is discussed in detail in a later section of this document.

2.3.5 Use of bonding agents

Commercial bonding agents are usually employed to improve the bond characteristics of the interface between the two layers. They help to improve the cohesion and integrity of the bond between the two surfaces. If bonding between the substrate and the overlay is not durable, water, de-icing salts may seep through the overlay to the 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, cleaned of any dust and/or unsound concrete particles before application of suitable bonding agent (Silfwerbrand et al. 2011).

Studies show 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. The grout has a higher water-cement ratio that reduces the strength and induces risk of a cohesive failure within the bonding agent itself. It is advised to use them for very stiff mortars so that they can properly fill the pores/grooves on the substrate surface for better interlocking and bond strength. Methods like scarifying and acid etching are used to create grooves to prepare the surface for receiving the overlay.

The two standard types of bonding agents that are common in the construction industry are – latex emulsions and epoxies. The latex emulsions consist high water content and suit cementitious compositions. It is recommended that some cement material be used with latex to avoid formation of a film in the bonding layers that produces a potential failure plane. Styrene Butadiene (SBR) latex is a copolymer that is compatible with cementitious compounds. This latex can coagulate if subjected to high temperatures, freezing temperatures or any repetitive mechanical action. Polyvinyl acetate latex (PVA) is available in non-re-emulsifiable or emulsifiable content. The non-emulsifiable PVA is a good binder for cementitious compounds whereas the emulsifiable PVA is mostly used as a bonding agent for plaster material to concrete surfaces.

Of the different commercial bonding agent products available in the market, the research team thoroughly reviewed four products that are widely used in the industry during the course of this study. These bonding agents serve in providing an effective bond between the substrate and the overlay. The properties and specifications for the four bonding agents reviewed are described below:

2.3.5.1 Euclid Chemical – Dural Prep AC:

Euclid Chemical – Dural Prep AC is an in-situ bonding agent with an anti-corrosion coating for the reinforcing steel. It is a water based epoxy bonding agent that is combined with Portland cement to form a bonding agent for freshly poured concrete over an existing, hardened substrate material. The product comes in three components – Part A, B and C. This products also functions as a corrosion inhibitor and is especially recommended when the overlay concrete is to be poured on existing concrete with exposed reinforcing steel. Its main advantage is its long open time, anti-corrosion properties and the relative ease of application. Below is some of the technical information for this bonding agent as given in the product data sheet.

PROPERTY	RESULT
Mix Ratio	1 gal A:1 gal B:36 lbs C (3.8 L:3.8 L:16 kg)
Contact Time	Up to 24 hours depending on temperature
Pot Life, 2 gal (7.6 L) unit, minutes	35 to 40
Compressive Strength, psi (MPa) ASTM C109	3 days: 2,900 psi (20 MPa) 7 days: 4,100 psi (28 MPa) 28 days: 4,500 psi (31 MPa)
Flexural Strength, psi (MPa) ASTM C348	28 days: > 1,280 (8.8)
Shore D Hardness ASTM D2240	90 to 95
Bond Strength, 7 days, psi (MPa) ASTM C882	1 hr open time: 2,480 (17.1) 24 hr open time: 2,700 (18.6)
Split Tensile Strength, psi (MPa) ASTM C496	28 days: > 600 (4.1)
Water Vapor Transmission ASTM E96	0.16 grains/hr•ft²
Appearance/Color	Concrete Gray

Figure 1: Technical Information for Euclid Chemical – Dural Prep A.C.

As discussed before, application of any bonding agent is not a substitute for good surface preparation to achieve a good overlay bond. Prior to application of this product on the substrate as a bonding agent, the surface must be cleaned thoroughly and should be free of any grease, oil, dust particles and other contaminants. The surface should also ideally be saturated, surface-dry before applying this bonding agent. Once the substrate is saturated surface-dry and free of any dust particles, one coat, between 20 and 27 mils thick, of this product is applied using a stiff brush. It can also be applied by using a hopper gun at a rate of 60 to 80 ft²/gal. Once the bonding agent is evenly spread on the substrate surface, it is allowed to dry for approximately one hour and subsequently the overlay concrete is poured.

2.3.5.2 Edison Coatings, Inc. – Flexi-Bond 540

Flexi-Bond 540 is a two-component, epoxy bonding agent used when applying new concrete surfaces over existing substrate concrete. Figure 2 shows some technical data for this product as obtained from the product data sheet.

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PROPERTY	VALUE
Composition	Modified Epoxy with Adhesion-Promoting Additives
Viscosity	Approx. 450-700 cps
Mix Ratio	3:1 by volume
Pot Life*	20-30 mins. At 70^0F
Tack-Free Time*	16-24 hrs., unaccelerated 8-12 hrs., accelerated
Bond Strength	>500 psi, (Cohesive Failure in substrate)
VOC	Essentially "Zero"

Figure 2: Technical Data for Flexi-Bond 540

The concrete substrate should be free of any hydrostatic pressure, moisture vapor transmission, dust and any other deleterious particles before applying this bonding agent. The surface should also cleared free of any laitance by mechanical abrasions as part of its treatment before making use of the bonding agent.

The application of this product on the substrate is similar to any other product. The resin and hardener are mixed for a period of 3 minutes in a 3:1 volume ratio and then applied by brush, squeegee or roller 30 minutes to 4 hours before pouring the overlay concrete. The nominal coverage rate for this product is 100 – 200 square feet per gallon. The overlay concrete can be poured typically within 8 – 12 hours of applying *Flexi-Bond 540* and within 4 hours in warmer weather. One key limitation of this product is that its functionality is adversely affected if the temperature drops below 7° C, or when the temperature of the overlay concrete, air or substrate is expected to fall below 7° C within 8 hours of application of this product.

2.3.5.3 Sika Armatec - 110 EpoCem

Sika Armatec – 110 EpoCem is a cementitious epoxy resin compensated three-component that along with other applications, also finds use as a bonding agent for fresh concrete poured over old, hardened concrete. This product also has corrosion inhibiting properties and is used as a protective layer over steel reinforcement. It has a high shear strength value and is applied over

the substrate by using a brush or a spray gun. Figure 3 shows technical information about this product as provided on its data sheet.

Compressive Strength	3 days	4,500 psi (31.0 MPa)	(ASTM C-109)
	7 days	6,500 psi (44.8 MPa)	73 °F (23 °C)
	28 days	8,500 psi (58.6 MPa)	50 % R.H.
Flexural Strength	28 days	1,250 psi (8.6 MPa)	(ASTM C-348)
			73 °F (23 °C)
			50 % R.H.
Splitting Tensile Strength	28 days	600 psi (4.1 MPa)	(ASTM C-496)
			73 °F (23 °C)
			50 % R.H.
Tensile Adhesion Strength	**Bond of steel reinforcement on concrete**		
	Sika® Armatec® 110 EpoCem coated	625 psi (4.3 MPa)	(ASTM C-1583)
			73 °F (23 °C)
	Epoxy coated	508 psi (3.5 MPa)	50 % R.H.
	Plain reinforcement	573 psi (4.0 MPa)	
Slant Shear Strength	**Bonding agent properties** (14 d. moist cure, plastic to hardened concrete)		
	Wet on wet	2,800 psi (19.3 MPa)	(ASTM C-882)
	24 hr. open time	2,600 psi (17.9 MPa)	73 °F (23 °C)
			50 % R.H.
Permeability to Water Vapor	Control	7.32×10^{-10} ft/sec	
	145 psi (10 bar)	8.92×10^{-15} ft/sec	
Diffusion Resistance to Water Vapor	$\mu\ H_2O\ {\sim}100$		
Permeability to CO2	$\mu\ CO_2\ {\sim}14{,}000$		
Corrosion Test	**Time-to-Corrosion Study**		
	• Sika® Armatec®-110 EpoCem more than tripled the time to corrosion		
	• Reduced corrosion rate by over 40 %		

Figure 3: Technical Information about Sika Armatec – 110 EpoCem

Prior to application of bonding agent, the substrate should be cleared of any dust, loose material, and other contaminants potent of reducing the obtained bond strength. In addition, it is to be ensured that the substrate is saturated surface dry without any standing water during the application of the product.

The product has three components – Component A (white liquid), Component B (Colorless liquid) and Component C (Gray powder). For its application, liquid components A and B are poured into a mixing vessel for 30 seconds followed by addition of Component C. Subsequently, the three components are mixed together continuously for a minimum period of 3 minutes avoiding formation of any lumps. The mix is applied using a stiff-bristle brush or broom with a

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minimum layer thickness of 1/64 in. The overlay concrete can then be poured over the substrate onto the bonding slurry while it is still wet.

2.3.5.4 Enecon – Eneclad Superbond

Enecon – Eneclad Superbond is a two-component, polymer composite with strong adhesive properties and finds use as an agent to bond new concrete to an existing concrete layer. As per the product data sheet, this product when applied to dry concrete provides a direct tensile bond strength of 400 psi by using the standard pull-off test as per ASTM D-4541.

The substrate should be cleared of any loose material(s) and surface contamination prior to application of *Eneclad Superbond*. The substrate should also be cleaned with a suitable solvent such as MEK, acetone, denatured alcohol or isopropyl alcohol to avoid leaving any residue on the surface. The product has two components – Base and Activator that are mixed in a ratio of 10:1 by weight and blended for 3-4 minutes to create a uniform, consistent mix. The coverage rate per kg of this product is 40-45 ft^2 of substrate area. The mix is applied on the substrate by using a stiff brush or short nap roller at a minimum thickness of five mils. The mix has a working life of 45 minutes for an ambient temperature of 25° C and should be applied within that period after it is mixed.

Figure 4: Components of Enecon – Eneclad Superbond

The research team decided to proceed with Enecon – Eneclad Superbond for use in the experimental study after careful review of all four products. The decision was supplemented by

additional information received from its vendor. German Cement Works Association (VDZ) had used this product and completed the test runs to verify the bond strength capacity between old and new concrete using this product. The product was used as the adhesion agent on old standard concrete quality (European load class C30/37), frequently used for construction and heavy duty road surfaces that was to be covered with same, fresh concrete quality. The institute conducted tensile tests on the various test bodies and all of them ended up with adhesion failures on either of the two concrete layers. In no case, adhesion failure occurred in the Superbond.

2.4 Steam-curing process

In this experimental study, ASTM C150 Type III cement that is used for the underlay part is subjected to a steam-curing regime for quick attainment of the design compressive strength. The Type III cement has a higher Blaine value, a value that represents the fineness of the cement particles. The increased fineness of the particles allows them to hydrate at a much faster rate and attain up to 70% of the design 28 days strength in less than 24 hours (Lee, C. et al. 2016). Moreover, use of Type III cement results in energy conservation during the steam-curing process in that it allows same strength development for a reduced temperature and process duration. Thus, use of this cement type is a very standard practice in precast prestressed concrete industry.

In the literature, it is found that a maximum temperature between 60°C and 70°C and a delay period of three to five hours are optimal values for the steam-curing regime. Also, it is proposed that the rate of temperature increase of the specimen should be between 22°C/hour and 33°C/hour for optimal strength results without experiencing any excessive volume changes in the specimens (A.A Ramezanianpour et al 2013), (Evan Gurley, Precast Inc. Magazine, National Precast Concrete Organization, 2011 May-June).

2.5 Materials for overlays

Silfwerbrand et al. (2011) stress on 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. Thus, concrete that has self-consolidating properties is very helpful to develop good interfacial bond strength. In addition, the research team argue against use of very 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 the substrate surface that is

saturated surface dry. In a study by the Swedish National Road Administration, it is 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 is recommended.

The concrete mix design to be adopted in the experiment conforms to the specifications of the Maryland State Highway Administration manual. In the concrete mix design, the proposed maximum size of coarse aggregates is 1⁄2 in. This is consistent with the responses received from other state highway administration. The state of Oregon, for example, recommends maximum aggregate size of 3⁄4 in.

Use of some other materials for concrete overlays is made by few states. For instance, New Mexico recommends use of polyester concrete overlay (Kwikbond for example) for constructing and repairing bridge decks. Indiana Department of Transportation, on the other hand, recommends use of latex modified concrete as the overlay material. The specifications of the same are in accordance with clause 722.09 in their manual.

2.6 Testing of bond between overlay and substrate

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

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

Shear test methods involve applying shear forces parallel to the interface. However, if the test specimen consists of two parts, as is the case with shear block tests, a bending moment is developed as soon as the load is applied. Delatte et al. (2000) reported issues with eccentricity

using shear block tests developed by Choi (1996), which resulted in lower bond values. To solve this problem, a test method consisting of three parts is used. However, these test methods also have the disadvantage of having two interfaces instead of one, which hardly exists in reality (Silfwerbrand et al. 2011). Ray et al. (2005) developed a test based on ASTM D905 (shear bond test for adhesives) that evaluates the interface performance of bi-layer composites through direct shear without the load being applied directly at the interface. They achieved consistent results for bond strength for commonly used overlay materials, however there were issues with rotation of specimen at high bond strengths. The guillotine test method solves the problem of moments and two interfaces, and has been used extensively (with some success) for measuring concrete-to-concrete bond despite the difficulty in aligning the bond plane precisely to eliminate bending. (Delatte et al. 2000; Wade et al. 1995).

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

2.6.1 Double-L test

In research conducted by *Strategic Highway Research Program (SHRP),* an experiment is done to determine the interfacial bond strength of two concrete layers using a Double L Test (Figure 5). In this method, two L shaped concrete specimens – one cast using Type III cement and subjected to steam-curing process to simulate action of the pre-stressed underlay slab and the second one is the equivalent of the overlay slab cast using Type I cement and conventional 28 days curing process. They are bonded face to face as shown in Figure 5. This method allows us to predict behavior of the concrete overlay on the new/existing prestressed concrete bridge deck.
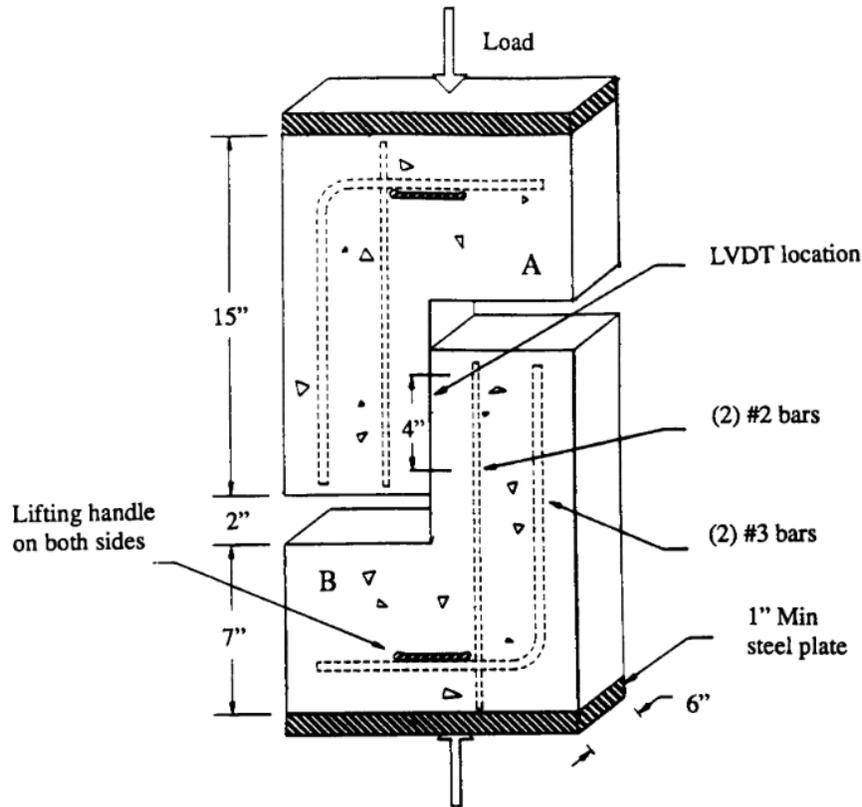
Figure 5: Typical test setup for the Double-L test

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

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

The lower segment that represents the prestressed deck is cast using Type III cement and subjected to steam-curing process described in detail in a later section. The upper segment that represents the bridge overlay is cast using Type I cement and subjected to 28 days normal moist-curing process.

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The specimen is inserted into the testing machine and the load value at failure is noted. The failure load is divided by the area of the bonding surface to compute nominal bonding stress. In this case, nominal bonding area is equal to 40-inch squares.

Nominal bonding stress = (Failure load in kips)/ (40 in^2)

2.6.2 Slant Shear Test

The slant shear test (Figure 6) measures the bond strength under a combination of shear and compression. This test method is described in detail in ASTM C 882/C 882M-05. It is used to determine the bond strength of bonding systems for use with concrete. Epoxy system is used to bond together two identical cylindrical sections of - 3 by 6-inches. The bonding area is at an angle of 30° with the vertical line. Once the specimen is cured, the test is performed to determine the compressive strength of the composite cylinder. The specimens are tested at the standard temperature of 73 $\pm$ 2 °F in compression. The total load carried by the specimen at failure is recorded and it is divided by the bonding area to get the bond strength of the composite cylindrical specimen. If any voids are found in the bond on inspection after test, reduce the area of the bonded area used in preceding calculations so as to account for these voids. In this reduction, neglect any voids that are not larger than ⅛ inch.

Several researchers have indicated shortcomings with this test (Silfwerbrand et al. 2011) due to unrealistic loading conditions, while others have highlighted its sensitivity to surface roughness of the underlying concrete (Júlio et al. 2004) – an essential component of bond strength. In the slant shear tests (Júlio et al. 2004), significant coefficient of variations were observed between different surface roughness conditions such as wire-brushing, partially chipped, partially chipped & pre-wetted and sand-blasting that are employed in the test.
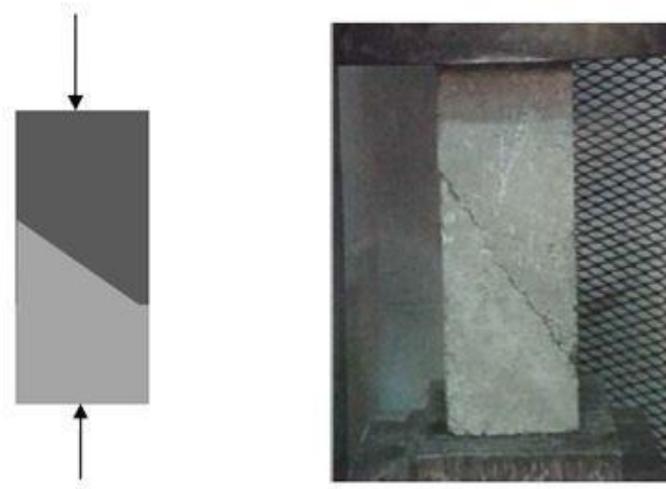
Figure 6: Slant Shear test setup

2.6.3 Push-off test

The push-off test (Figure 7), 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 (Fig. 2) to evaluate shear transfer across bonded concrete overlay interfaces reinforced with power driven nails. In their proposed method, two PVC pipes are embedded into the cast overlay concrete with a high-strength threaded steel bar inserted through each pipe. One end of the threaded bar is connected to a front loading head, while the other end is tightened against the back of a mild steel plate.

Two hydraulic cylinders are used to apply loads at the back side of the overlay through the steel back plate along the centerline of the interface to apply shear to the interface. In their set-up, there was a small eccentricity (20mm) because the centerline of the steel bars was not right at the interface, but they considered this moment negligible.
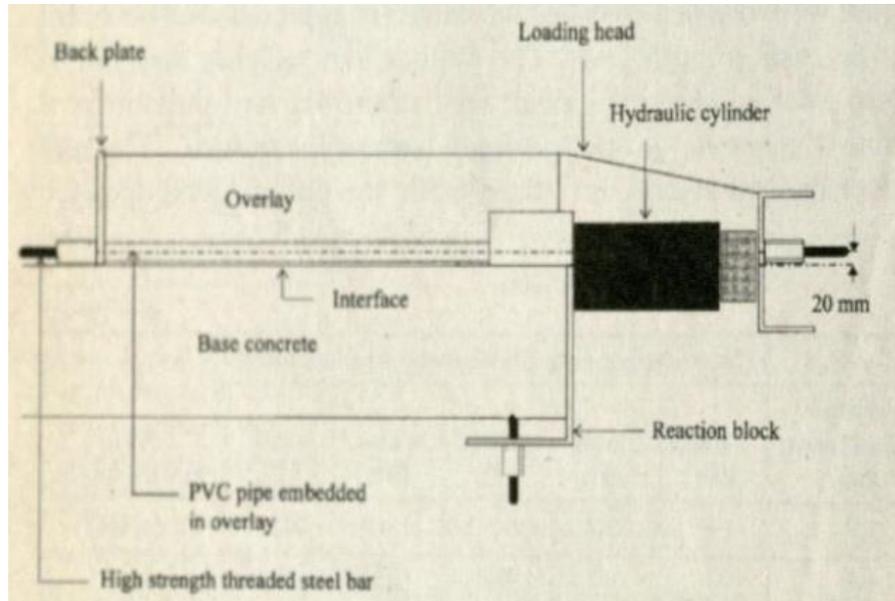
Figure 7: In-situ push off test: alignment of interface and hydraulic cylinders (Choi et. al, 1999).

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

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 higher for overlay specimens with nails. This is attributed to the redistribution of stresses across the interface surface after the adhesion was lost. Many overlay specimens with nails prematurely failed in low-strengths concrete (base concrete or overlay) before the interface failure.

These observations indicate that the interface shear strength of overlay specimens with nails is lower than those without nails. Insufficient interface preparation leads to a reduced interface shear strength in these tests. Interface strength of cracked specimens was lower than that of uncracked specimens.

2.6.4 Split Prism Test

The split prism test (Figure 8) is a standard test for quantifying tensile strength of prismatic concrete specimens. It is also known as splitting tensile test. In our experimental setup, two halves of split prism – one cast with Type III cement and subjected to steam-curing regime and the second with Type I cement subjected to normal moist-curing for 28 days are used. The size of each half in the specimen is 6 in. x 6 in. x 3 in.
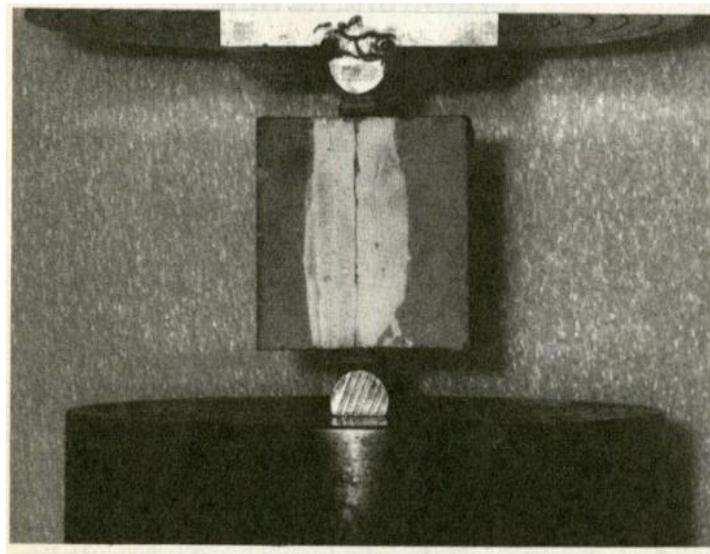
Figure 8: Split Prism Test Setup

2.6.5 Pull-off test

The pull-off test (Figure 9) is outlined in ASTM C1583-04. It is a direct tension test; the composite specimen is pulled apart by loads perpendicular to the bonded interface. In this test, a shallow core is drilled through the substrate perpendicular to the surface and a steel disk is attached to the top face of the specimen. The disk is subjected to a tensile load until the specimen fails when the corresponding load is noted to compute the tensile strength of the interface. In this method, the load at the failure of the specimen is governed by the region where the failure occurs along the path of the load.

Preparation of Test Specimen - Drill to at least 10mm [0.5 inch] below the concrete-overlay surface. Make sure that the surface is free of any standing water; clean the surface of any debris. Use the epoxy adhesive to attach the steel plate to the top face of the specimen. Apply tensile load at the standard constant rate (as indicated in ASTM C1583) concentric to the plate & 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. This load is divided by the bond surface area to compute the bond tensile strength.
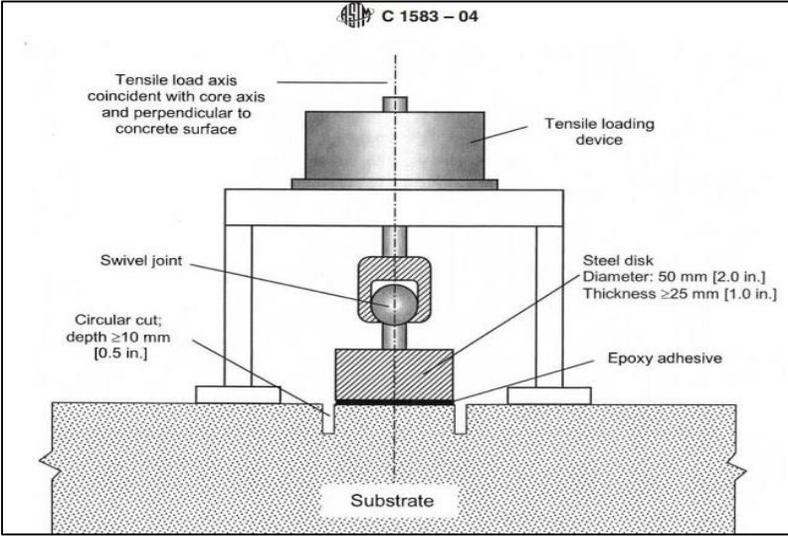
Figure 9: Pull-off test setup for checking tensile strength of substrate (ASTM C1583)

3 Methodology

3.1 Introduction

For this research project, two different sets of specimens were prepared for the Double-L and the Split-Prism specimens. For the Double-L test, an L-shaped underlay half is prepared over which overlay concrete is poured to get a cuboidal composite specimen. Similarly, for the Split-Prism test, a 3 in. x 6 in. x 6 in. cuboid underlay half is prepared with the overlay concrete poured on its side to get a 6 in. cube composite specimen.

3.2 Materials

3.2.1 Formwork

Owing to the unconventional shape of the concrete specimens, custom formwork was prepared using wood panels. Two different types of wood panels were used – ¼" thick Medium-density fiberboard panel and ¾" thick conventional wood lumber. The lumber was marked and panels were cut from it to the appropriate dimensions using a table saw.

L-shaped specimen – For the "L-shaped specimen", ¾" thick wood panels were used as side panels and ¼ in. thick Medium-density fiberboard panels were used as the bottom panel.

Figure 10: Formwork for L-shaped underlay specimens

Cuboidal specimen (For Double-L overlay) – For the cuboidal specimens, ¼ in. thick Medium-density fiberboard panels were used for the long side panels and ¾ in. thick wood panels were used for the short side panels and the bottom panels. The assembled formworks for both test-setups are shown in Figure 11 below.
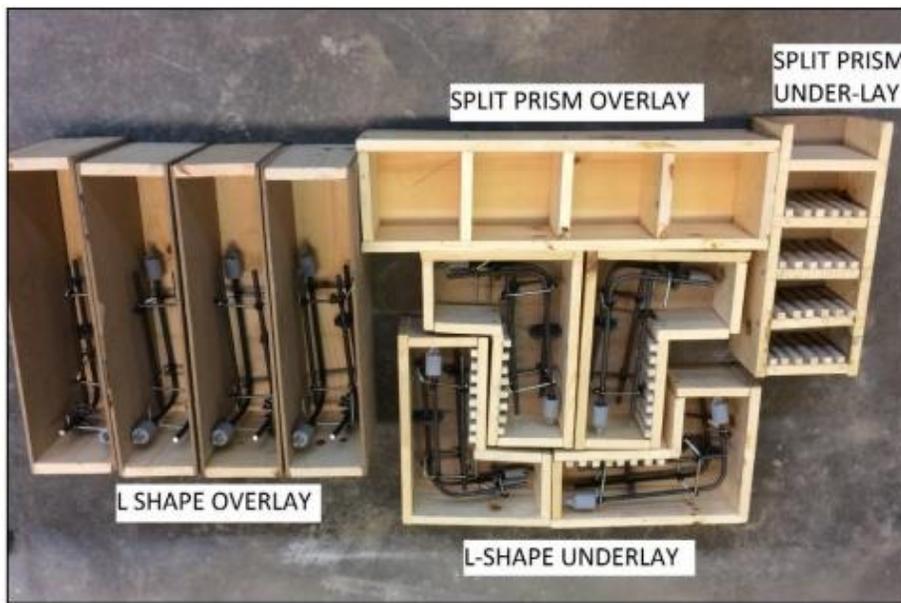
Figure 11: Assembled formwork for different concrete specimens

3.2.2 Cement

Portland cement was used for both the underlay and the overlay halves for all the 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 regime helps in accelerated strength development. For the overlay half, conventional Type I cement is used. The use of the respective cement types is done to closely simulate the actual field conditions where the precast prestressed slabs employ use of Type-III cement for quick turnaround and the concrete overlay mix employs use of Type I cement.

3.2.3 Coarse Aggregates

No. 8 stones (Figure 12) were used as coarse aggregates for the concrete mix. The use of this gradation allowed for a good workable mix for good flow inside the grooves, especially in the congested space around the reinforcement in the L-shaped specimens. Also, a sieve analysis of a representative sample of the coarse aggregates was carried out; the results are as indicated in Table 1 below.

Table 1: Results for sieve analysis of coarse aggregates

Sieve Size	1 in.	¾ in.	½ in.	3/8 in.	No. 4	No. 8
Weight retained (grams)	-	-	45.6	953.2	3407	466.4
Weight of aggregate finer than (%)	100	100	99.09	80.02	11.88	2.56

To account for the effect of surface moisture on the coarse aggregates on the concrete mix design, moisture content of the aggregates was worked out. Over the course of the project, the moisture content remained very consistent and the same value was used for all mix designs.

The results from the test are as indicated in Table 2 below.

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

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

Figure 12: No. 8 stone used as coarse aggregates for the mix

3.2.4 Fine Aggregates

Manufactured sand (Figure 13) acquired from one of the nearby quarries in Maryland was used as the fine aggregates in the concrete mix design. Like the coarse aggregates, the moisture content of the fine aggregates remained consistent over the course of the project and the results are indicated in Table 3.

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

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

Figure 13: Manufactured sand used as fine aggregates for the mix

3.2.5 Admixtures

Two admixtures were used in the concrete mixes for both the underlay and the overlay halves of the specimens. First, air-entraining admixture *Sika AE-14* was added to ensure sufficient air-entrainment as required in the state highway manual. This admixture was added to the water prior to its addition to the mix design constituents. Secondly, water reducing admixture *Sika Viscocrete 2100* was used in different doses for the underlay and the overlay halves to correspond to the required workabilities. The dose was higher for the underlay half owing to two factors – use of Type III cement that made the mix very stiff and requirement of a lower water-cement ratio of 0.34 for this mix. The admixtures used are shown in Figure 14.
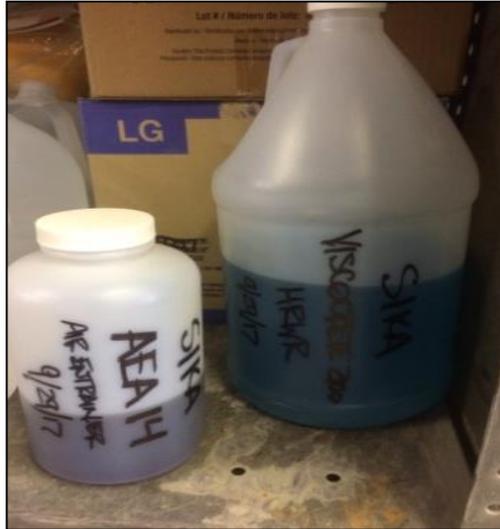
Figure 14: Admixtures – Sika AE14 and Sika Viscocrete 2100

3.3 Mix Design

The mix design specifications for the underlay concrete pour conform to the specifications used by the Northeast Prestressed Products, LLC plant in Cressona, Pennsylvania. The specifications allow rapid development of concrete strength owing to the usage of ASTM Type-III cement and an 18-hours steam-curing regime. Below are the specifications adopted for the mix:

Type of Cement: **ASTM Type-III cement**

Fine Aggregates: **Manufactured Sand**

Coarse Aggregates: **No. 8 stone**

Water-Cement Ratio: **0.34**

Air-entraining admixture: **SIKA AEA-14 – The dosage adopted is 2.5 fl. Oz per 100 lbs. of cement to entrain 5.5% of air in the mixture.**

Plasticizer: **Sika Viscocrete-2100 – For 1.6 cubic feet of mix size, 80 ml of admixture is added to the mix.**

The target slump value for the underlay mix was set at eight (8) inches. Owing to the rapid hardening of Type-III cement in the mixes, ensuring that the concrete is properly compacted around the reinforcement region and that it fills the grooves properly proved to be challenging.

An underlay pour for any given case (of the seven cases) comprised of two mixes. The first mix included four L-shaped specimens and three 4 x 8 standard cylinders. The batch size for the first mix was 1.6 cubic feet. The second mix included four 3 x 6 halves of split-prism specimens and three 4 x 8 standard cylinders. The batch size for this mix was around 0.6 cubic feet.

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 is around 8500 psi. The individual strengths for different mixes are tabulated in a later section. The mix design specifications for the mixes are indicated in Table 4 below.

Table 4: Mix design specifications for the four mix types

Mix	L-shape underlay sample	Split-prism underlay sample	L-shape 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 (ml)	9822	3919	9772	3900
SIKA AEA 14 (ml)	47	18	42.07	15.8
Sika Viscocrete 2100 (ml)	64	25	----	-----

For each concrete mix, a slump test for the freshly mixed concrete was done to ascertain if the workability corresponds to the requirements as per the SHA specifications. For both the underlay and the overlay halves, the slump values were in the acceptable range.

3.4 Sample Preparation

3.4.1 Underlay Samples

For the underlay half, custom specimens were prepared in the NRMCA lab using the available equipment. Custom specimens were a necessity given the unconventional shapes of the concrete specimens, especially the two L-shaped halves required for the shear test. The panels and the strips to be hammered on the inside of the bond panel to obtain a groove pattern were cut to a

close precision using the table saw at the lab. The cut panels were then screwed together at the lab.

The strips that needed to be nailed to the inside of the bond panel were required to be cut very precisely to get accurate groove configurations. Square shaped groove patterns of different widths – ¼ in, 3/8 in. and ½ in. were required for the different test cases described in detail in Table 6. For the initial trials, strips were cut from Medium-density fiberboard panels. However, owing to the 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 significantly during the curing regime resulting in the deterioration of the grooves.

Once the Medium-density fiberboard strips were replaced with the hardwood lumber strips, an improved groove configuration was observed in that the grooves were sharp edged and more precise in size. In Figure 15 below, freshly prepared L- shaped underlay specimens are shown and the L-shaped underlay half after demolding is shown in Figure 16 below. Split-prism underlay half after 18 hours of steam curing is also shown in Figure 17 below.
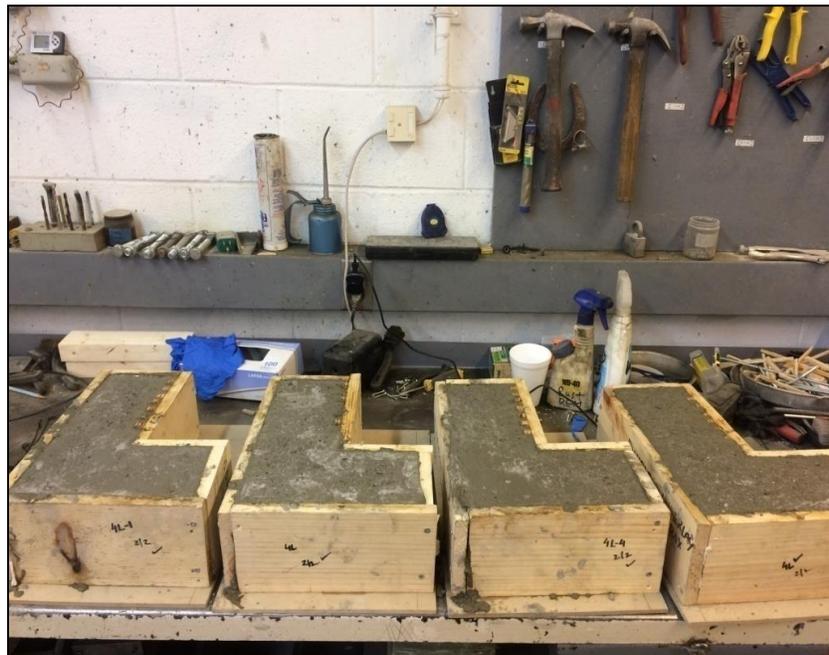
Figure 15: Freshly poured L-shaped underlay concrete specimens

Figure 16: L-shaped underlay half after 18 hours of steam curing

Figure 17: Split-prism underlay half after 18 hours of steam curing

For the shear bond strength test on the L-shaped specimens, it is to be ensured 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. However, for additional safety margin against failure of concrete, nominal reinforcement is provided in the L-shaped specimens. This is particularly important for the shorter horizontal leg of the specimen that 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 are provided as reinforcement. Two of the bars are straight bars that run along the longer side and the other two are L-shaped bars that also run along the longer side but take turn to also act as the top reinforcement bars for the shorter cantilever portion of the specimen. The bars help ensure adequacy against possible concrete cracking/crushing to ensure that the results reflect the bond shear strength.

In addition to the main reinforcement bars, two sets of ties are provided for each specimen, primarily to ensure that the main bars are held in place. The ties are quarter inch (1/4 in.) diameter bars; the small diameter allows for bending into an approximately 3 inch x 3 inch square for use as ties. They are bent using the hollow square metal rod while using the clamp apparatus at the lab to support the bars while being bent. Also, a U-shaped bar of appropriate length is cut from the same ¼ in. bar that is tied to the L-shaped bar at some point along the shorter side so as to hold them in place while pouring of concrete. Figure 18 shows a tied reinforcement cage assembly.

Figure 18: Reinforcement cage for the L-shaped halves

For the test case that involves application of bonding agent at the bond interface, commercial bonding agent *Enecon- Eneclad Superbond* is selected for use.

The specifications provided by the vendor that are laid out in the literature review section of this document are duly followed while applying the product at the interface of the underlay specimen prior to pouring of overlay concrete.

To ensure that the surface is free of any dust or loose particles, the same was cleaned by blowing air and subsequently by applying acetone over it. Only after the surface is found to satisfactorily

clean, the bonding agent was applied on it. The base and the activator are mixed thoroughly for 2-3 minutes prior to its application on the interface using the stiff brush provided.

Figure 19: Underlay half with bonding agent applied on the bond interface just before pouring of overlay concrete

For the last test case that involves application of shear studs through the interface, Tapcon concrete screw anchors of length 6 in. and diameter ½ in. were chosen for use (Figure 20). 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, equal to three inches. Holes with diameter slightly higher than the anchor diameter were drilled in the underlay bond panel with the anchors subsequently inserted horizontally, running three inches on either side of the panel as shown in Figure 20.

Figure 20: Tapcon anchors inserted in the bond panel

The formwork of the underlay half (Figure 21) is then assembled and the concrete is poured (Figure 22). It is then placed for the 18-hours steam-curing regime, as done for the other cases after which the sample is demolded.

Figure 21: L-shaped underlay half formwork with anchors in place prior to concrete pouring

Figure 22: Split-prism underlay half with freshly poured concrete

3.4.2 Overlay Samples

Formwork preparation for the overlay specimens was almost similar to the underlay halves with the exception of the panel sizes. For the L-shaped specimens, a cuboid of required size (5 in. x 10 in. x 20 in.) was prepared and the cast underlay half is placed in the cuboid. Reinforcement cage is placed appropriately and a Styrofoam block of size – 5 in. x 5 in. x 1 in. is placed that acts as the partition at the two faces perpendicular to the bond surface between the two pours. The underlay half with three in. length of anchors protruding out from the bond surface is then placed carefully in the composite specimen formwork (Figure 23), the reinforcement cage is placed, a Styrofoam block is placed for the partition and finally the overlay concrete poured (Figures 23 and 24). The sample is then placed in the curing room for 28 days of curing and subsequently demolded to get the composite specimen (Figure 25 and 26).

Figure 23: Underlay half with anchors protruding from the bond surface prior to pouring of overlay concrete

Figure 24: Composite specimen with freshly poured overlay concrete

Figure 25: Composite specimen for the Double-L test after demolding

Similarly, the split prism underlay half is placed in a 6 in. cube and overlay concrete poured on side of the underlay half to get a composite specimen (Figure 26). This sample is also placed for 28 days curing in the curing room at the NRMCA lab.

Figure 26: Composite specimen for the the Split-Prism test after demolding

3.4.3 Curing conditions

The steam-curing regime followed is consistent with the suggested practices recommended in the literature reviewed.

After pouring of the underlay concrete in formwork, a lag period of three hours is allowed to elapse before placement of specimens in the oven (Figure 28). The initial temperature of the oven is set at 30° C and is ramped to a final temperature of 60° C in one and half hour. The temperature is incremented by 5° C in every 15 minutes. Once the maximum temperature of 60° C is attained, it is allowed to stay at the temperature for 15 hours following which it is again brought down to 30° C at the same rate in one and half hour. Thus, the specimens are placed in the oven for a total duration of 18 hours. Figure 27 depicts graphically the steam curing regime followed. After the steam-curing regime, the formwork is demolded and the samples are allowed to cool for a duration of two hours. For the L-shaped and the split-prism specimens, the overlay concrete is poured after the samples have cooled to the room temperature. The cylinders are tested using the standard compression testing apparatus to record the average compressive strengths for the two batches – underlay halves of the L-shaped specimens and split-prism specimens.

It is to be noted that the lag period, also known as the preset time is an important factor controlling the strength development while the sample is steam-cured. For the initial trials, different values of preset 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 preset time of three hours was found to be optimum and followed subsequently. The results of the initial trials are listed in Table 5 below.

Table 5: 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	3480.00	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**

As observed from the table above, a 3-hours preset time is an optimum time interval. The average compressive strength for the three cylinders for this preset time (6272.5 psi) is also consistent with the MDOT SHA recommendation of 4500 psi minimum compressive strength for the underlay mix.
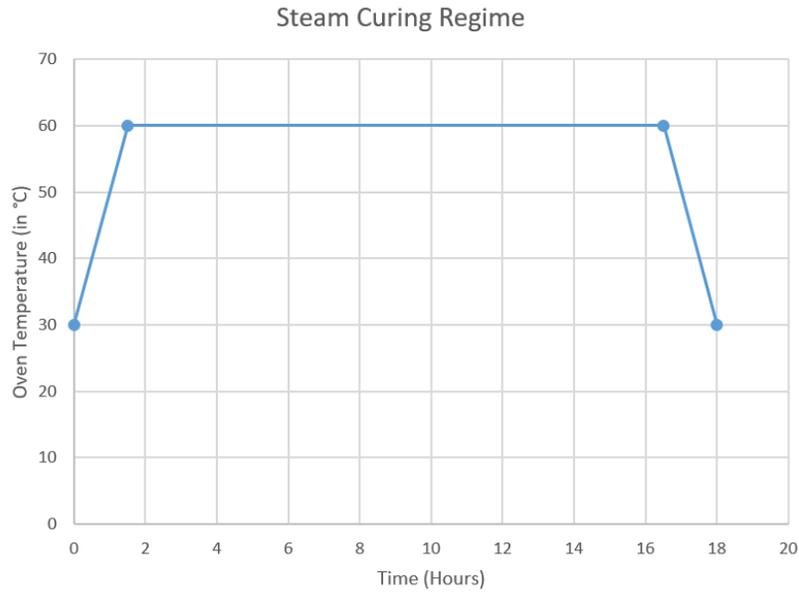
Figure 27: Steam curing regime for the underlay specimens

Figure 28: Underlay specimens placed in oven for steam curing

After the underlay halves are steam-cured, the overlay concrete is poured over the samples to get composite concrete specimens for both – Double-L test and split-prism test specimens. The composite samples are then placed for conventional curing (Figure 29) in the curing room at the NRMCA lab for a period of 28 days. The samples are tested after the 28 days period.

Figure 29: Composite specimens and 4 in. x 8 in. cylinders placed for 28 days curing

3.5 Test Procedures

3.5.1 Compressive Strength

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 half, the cylinders were placed in the oven for the steam-curing regime for 18 hours 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 half, four cylinders were cast for each mix and placed in the curing room for 28 days of normal curing. One of the cylinders was tested after 14 days and the remaining three were tested after 28 days. The compression test results for the same are tabulated in a later section of this report. Figure 30 shows a 4 in. x 8 in. cylinder after reaching failure in the compression test.
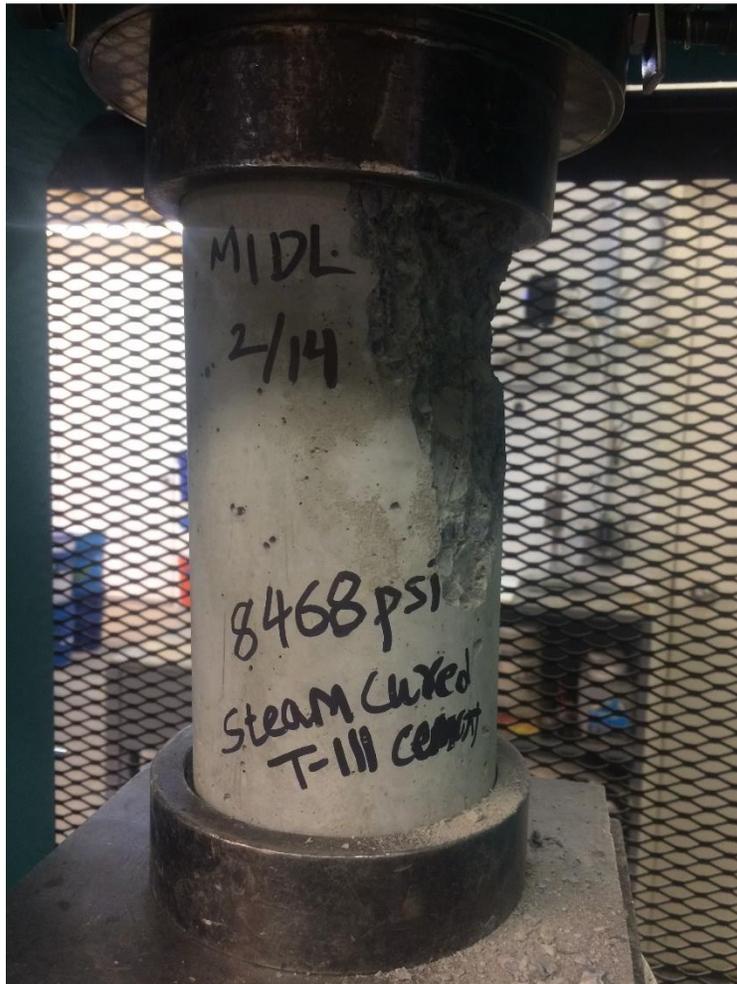
Figure 30: 4 in. x 8 in. cylinder placed for compression testing

3.5.2 Shear Bond Strength

The shear bond strength is evaluated using the Double-L test as described in a preceding section of this document. The composite arrangement is placed for testing in the standard compression-testing machine as can be seen in Figure 31. It is ensured that the centroid of the load is in line with the bond surface to ensure zero or minimal eccentricity. This helps in achieving a state of pure shear along the bond interface so that the failure load reflects the actual shear strength for

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the 8 in. x 5 in. bond interface. The load is applied using the standard rate of 30 ± 5 lb/s as referenced in the SHRP Paper.

Figure 31: Testing of composite specimen for the Double-L test (Shear Bond Strength)

In Figure 32, one half of an L-shaped specimen can be seen. It was observed as can be can be seen in Figure 32 that the failure occurs along the bond interface. Thus, the failure load reflects the shear bond strength for the Double-L specimens.

Figure 32: One half of an L-shaped specimen after shear bond failure

3.5.3 Tensile Bond Strength

The tensile bond strength is evaluated using the split-prism arrangement as shown in Figure 33 below. The composite cube specimen is placed such that the load is in line with the bond interface. The grooves are perpendicular to the direction of load. On reaching a certain load value, the cube splits in its two halves (underlay & overlay); this failure load (in lbs.) is divided by the bond area (= 36 sq. inches) to get the tensile bond strength (in psi). The load rate is maintained at 30 ± 5 lb/s.

Figure 33: Testing of composite specimen for the Split-Prism Test (Tensile Bond Strength)

As observed for the L-shaped specimen, the two halves of the split-prism specimens detach along the bond interface on reaching the failure load value (Figure 34). Thus, the failure load value reflects the strength of the tensile bond for the split-prism specimens.

Figure 34: Halves of a Split-Prism specimen after tensile bond failure

4 Results and Discussion

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

In this research work, surface roughness was the test parameter with seven (7) different surface roughness conditions tested altogether. The seven test conditions are mentioned in Table 6 along with the number of samples cast for each type.

Table 6: Description of research test parameters and specimen count

Test Parameter No.	Description of test parameter (Surface roughness condition)	No. of specimens prepared		
		L-shaped underlay & 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	3/8 in. x 3/8 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

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

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

As discussed before, three 4 in. x 8 in. cylinders were cast for each of the seven test conditions. The reading for the tests are reported in Tables 7 and 8 below for the seven test cases.

Table 7: Compressive strength test results for 4 in. x 8 in. cylinders for the underlay mix

Compressive Strength of 4 in. x 8 in. cylinders cast with the underlay mix (psi)								
Test Parameter 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 8: Compressive strength test results for 4 in. x 8 in. cylinders for the overlay mix

Compressive Strength of 4 in. x 8 in. cylinders cast with the overlay mix (psi)								
Test Parameter No.		**1**	**2**	**3**	**4**	**5**	**6**	**7**
Compressive Strength after 14 days of normal curing (psi) for Cylinder 1	**Cylinder 1**	5670.0	5156.0	5284.7	5259.3	5229.0	5120.0	6027.5
Compressive Strength after 28 days of normal curing (psi) for Cylinders 2, 3 & 4	**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 9 shows results for shear bond strength for the seven test conditions. Figure 35 is a plot of average shear bond strength for the seven test conditions and Figure 36 shows the one of the Double-L specimens after failure.

Table 9: Results for the shear bond strength test for the composite specimen

Shear bond strengths for the composite cuboid specimens (psi)								
Test Parameter No.		**1**	**2**	**3**	**4**	**5**	**6**	**7**
Shear bond strength after 14 days of normal curing (psi) for Specimen 1	**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 (psi) for Specimens 2, 3 & 4	**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
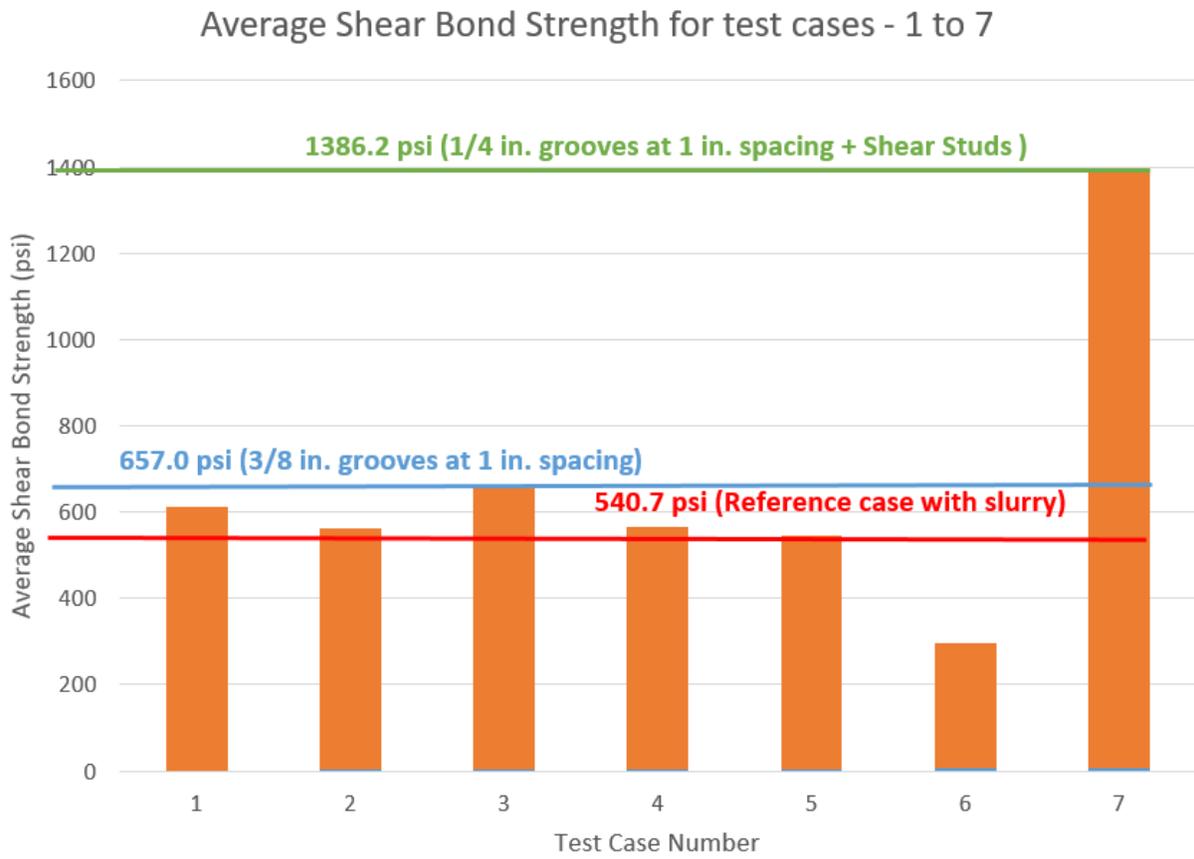
Figure 35: Comparison chart for the average shear bond strength for the seven test cases
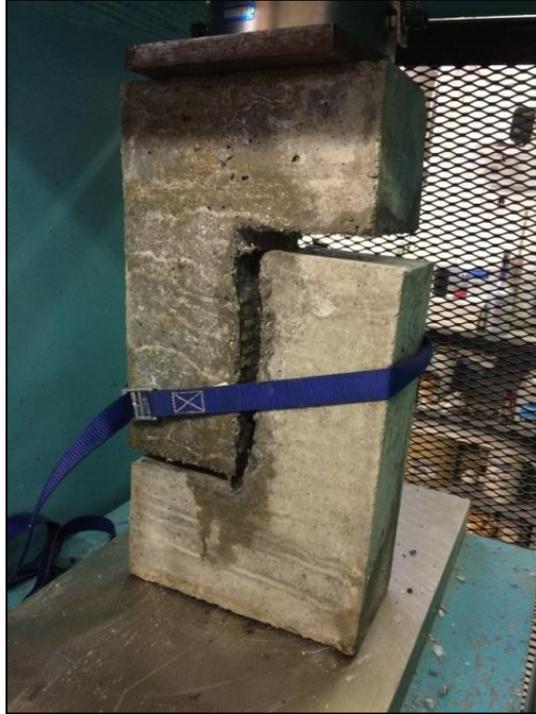
Figure 36: Composite specimen after reaching shear bond failure in the Double-L test

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

The bond tensile strength is tested by means of a split-prism tensile strength 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 condition involving use of shear studs. For that test case, 8 in. cubes comprising of two halves of 4 in. x 8 in. x 8 in. cuboids were prepared as 3 in. of penetration for the shear studs was required across both halves. The load is applied in a manner such that it is in line with the bond interface with the grooves perpendicularly to the load direction.

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. In addition, 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 specimens was tested at 14 days.

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

Three 4 in. x 8 in. cylinders were cast for each of the seven test conditions for the underlay mix and four 4 in. x 8 in. cylinders were cast for each test condition for the overlay mix. The readings for the tests are reported in Tables 10 and 11 below for the seven test cases.

Table 10: Compressive strength results for 4 in. x 8 in. cylinders for the underlay mix

Compressive Strength of 4 in. x 8 in. cylinders cast with the underlay mix (psi)								
Test Parameter 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 11: Compressive strength results for 4 in. x 8 in. cylinders cast with the overlay mix (psi)

Compressive Strength of 4 in. x 8 in. cylinders cast with the overlay mix (psi)								
Test Parameter No.		**1**	**2**	**3**	**4**	**5**	**6**	**7**
Compressive Strength after 14 days of normal curing (psi) for Cylinder 1	**Cylinder 1**	6102.0	5578.0	4565.4	5198.0	6861.2	5974.0	6085.4
Compressive Strength after 28 days of normal curing (psi) for Cylinders 2, 3 & 4	**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 done for the shear bond tests, four 6 in. composite cubes are cast for test cases 1 to 6 and four 8 in. composite cubes are cast for test case number 7 involving use of shear studs. The sample is placed to ensure that the load is in line with the bond interface for avoiding any additional stresses due to accidental eccentricity. The load value when the composite sample splits into the two constituent halves was recorded and divided by the interface area to get the split tensile strength results.

Table 12 shows results for tensile bond strength for the seven test conditions. Figure 37 is a plot of tensile bond strength for the seven test conditions and Figure 38 shows one of the split-prism specimens after failure.

Table 12: Results for the tensile bond strength test for the composite specimens

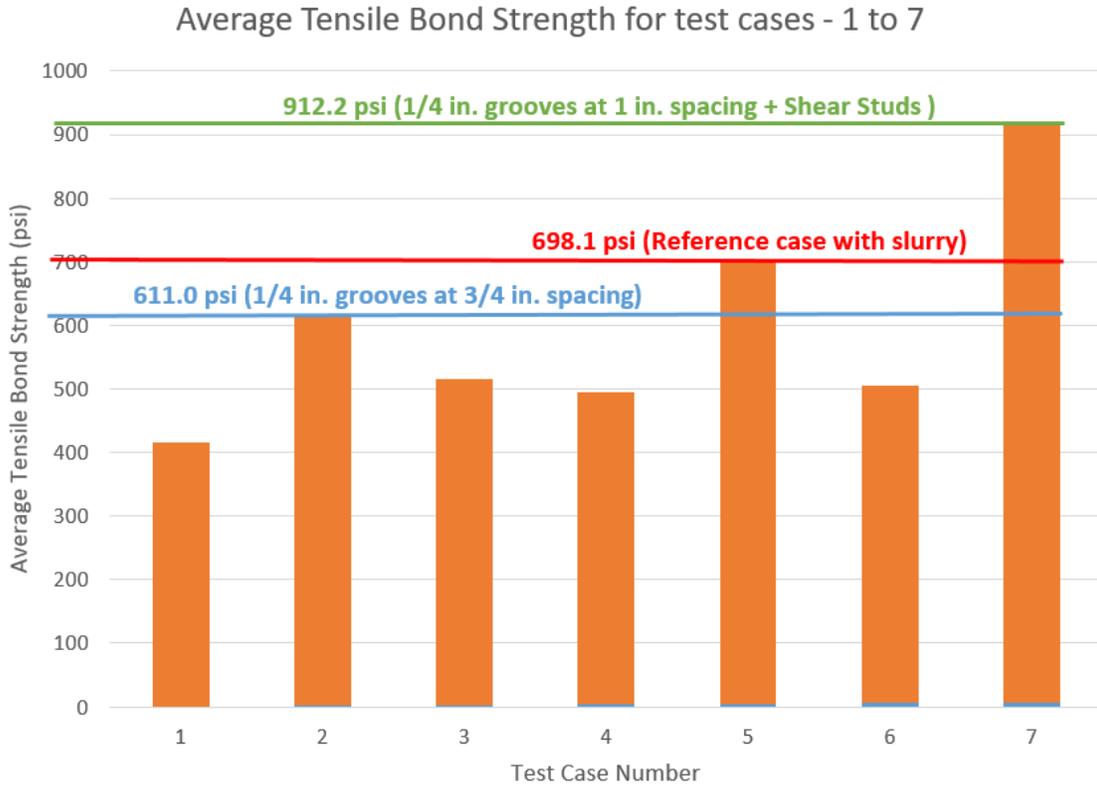| Tensile bond strength test results for the composite cube specimens (psi)								
Test Parameter No.		1	2	3	4	5	6	7
Tensile bond strength after 14 days of normal curing (psi) for Specimen 1	Specimen 1	520.0	471.4	436.7	277.2	630.0	542.8	876.7
Tensile bond strength after 28 days of normal curing (psi) for Specimens 2, 3 & 4	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 37: Comparison chart for the average bond tensile strength for the seven test cases

Figure 38: Composite specimen after reaching tensile bond failure in the Split-Prism Test

4.3 Discussion of test results

From the test results, it is observed that the test case number 5 that uses the cement-sand slurry mix at the bond interface in addition to the ¼ in. grooves at 1 in. spacing has the minimum shear bond strength value of all test cases, except test case number 6 that uses *Enecon Eneclad Superbond* bonding agent. For both cases (test cases number 5 & 6), the use of slurry and bonding agent formed a potentially weak layer at the interface. The weak layer formed in both cases leads to early failure in both cases when compared against the other five test cases in case of shear strength tests.

The key takeaway is the improved shear strength characteristics for the bond when grooves are introduced along the interface. The grooves along with good surface preparation procedures help develop a good interlocking effect and improve the performance of the overlay bond in shear. Another important observation noted from the experiments is that the average bond tensile strength values for the first four cases that have grooves running along the interface are reduced values in comparison to the one obtained for the reference case with slurry mix. The tensile bond strength results for the case with bonding agent are comparable to the first four case that do not use any additives other than the groove configurations. This indicates that the bonding agent did not affect the tensile strength of the bond in any significant manner. However, the average bond tensile strength values for all cases other than the reference case are still higher than the recommended value of 233.0 psi for 20-year performance of concrete overlays as per Sprinkel M. (1993). In field tests done on fourteen bridge decks with latex-modified concrete (LMC) overlays by the Virginia Department of Transportation (VDOT), the average tensile rupture strength for LMC overlays was 233 psi. In addition, 68 percent of the failures occurred in the base concretes indicating that the bond strength was still higher than the recorded values for those cases. 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.

The test case that involves application of shear studs with equal embedment across both interfaces reported the highest average values for both tests – shear bond strength (1386.2 psi) and tensile bond strength (912.2 psi). On expected lines, the addition of shear studs results in a significant improvement in the bond strengths for concrete overlays on the underlying slab.

Therefore, shear studs can be used to provide additional strength margin provided they could be installed in a practical manner.

5 Conclusions, recommendations and future work

5.1 Conclusions

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 are the most important factors to achieve a good bond between the overlay and the prestressed slab. Thus, seven different test cases were established; one of them being the reference test case that uses application of slurry mix to achieve a good overlay bond. Of the remaining six test cases, four cases simply involved application of different groove configurations along the interface, one case involved use of 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 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 full conformance to the current practices adopted by the industry and MDOT SHA in its projects. 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 test setups, it was ensured that the load applied by the testing machine is in line with the interface to avoid any additional stresses along the interface. Each specimen was subjected to load until it failed and the recorded load value was divided by the interface area to get the failure shear and tensile stresses for the bond in the two tests setups. 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 cases, they were checked against the values obtained for the reference test case that uses slurry and recommendations followed.

The results obtained from this experimental study are very positive concerning possible use of prestressed slab panels with pre-existing grooves over which the overlay concrete can be directly poured. The average bond shear strength values for all the four test cases that simply 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. It was found that the interlocking effect obtained through these grooves contributes significantly to the bond shear strength. For the tensile strength tests, the values for the cases with grooves are lower than the reference case but are still higher than the threshold

value of 233.0 psi for good 20 years performance of concrete overlays (Sprinkel M; 1993). It is also noted that the use of bonding agent has a negative impact on the shear bond strength due to formation of a weak layer at the interface. Therefore, the use of bonding agents to achieve good bond between the concrete overlay and the underlying slab is an area that warrants further research and is not recommended for now. The use of shear studs can be made to further increase the shear bond and tensile bond strengths for concrete overlays. However, the installation of these studs across the underlying slab and the overlay requires further considerations due to implementation issues at site.

5.2 Recommendations

On basis of the results obtained in this project work, the research team recommends the use of precast planks with pre-existing grooves manufactured at plants in future projects of the MDOT SHA. As noted before, providing groove configurations on the deck slab that run transverse to the traffic direction significantly improve the shear characteristics of the bond between the overlay and the deck. The average values of shear strength for all the four test cases that only have grooves without any additives are higher than the case in which slurry mix was used to simulate the current practice followed by MDOT SHA. The current practice is highly cumbersome as discussed before in this report. If the recommendations made in this report are followed, the use of slurry mix could be eliminated altogether prior to pouring of overlay concrete. Precast panels with grooves manufactured at plants could be readily used at site, the top surface with grooves is cleaned thoroughly with existing methodologies available and finally the overlay concrete is directly poured over the slab. The grooves help create an interlocking effect and improve the bond performance of the overlay. As evidenced in test case number 7, addition of shear studs help further improve the shear bond and tensile bond but may not be easy to implement.

5.3 Future Work

- 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.

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