THE EFFECTS OF COMMON SURFACE PRETREATMENTS ON THE SHEAR STRENGTH OF BONDED CONCRETE OVERLAYS

by

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Thesis directed by Associate Professor Frederick R. Rutz

ABSTRACT

The durability of a concrete repair is highly dependent on the shear strength of the interface between new and old concrete. Therefore, the engineer designing the repair makes every effort to maximize this strength. To that end, pretreatments, such as prewetting the substrate and/or applying bonding agents, are commonly specified. The efficacy of these pretreatments is often debated, and previous studies have produced contradictory results. This research was undertaken to determine the effects of prewetting the substrate and applying a bonding agent, both in combination and individually. The bond strength in tension and the shear strength of the bond were measured using a variety of methods, including in-place testing and testing of extracted specimens. The results indicate that both prewetting and the use of a bonding agent can be beneficial to the shear strength of bonded overlays.

The form and content of this abstract are approved. I recommend its publication.

Approved: Frederick R. Rutz

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OVERVIEW

1.1 Introduction

When damage or deterioration to existing concrete is not so severe as to warrant complete removal, repairs frequently involve overlaying the existing concrete with a new concrete surface. Examples of this type of repair range from small patches on a wall or beam, to resurfacing existing concrete pavement or a bridge deck with a layer of new concrete. In the case of pavement, it is possible to design the new concrete to act independently from the existing concrete. However, it often much more economical to bond the new concrete, hereafter referred to as the overlay, to the existing concrete, hereafter referred to as the 'substrate'. When sufficient bond exists between the overlay and substrate, the two slabs will act in unison under applied loading; this behavior is known as "monolithic" action (Bissonnette, et al., 2012). The durability of the repair, whether a patch in a structural member or an overlay of existing pavement, is highly dependent on the shear strength of the bonded interface between the overlay and substrate.

The desire to obtain good bond strength to prolong the life of a repair is apparent, and much time and effort has been spent to isolate the factors that produce consistently high bond strengths. This research examines two such factors which are the cause of significant debate within the engineering community: 1) prewetting the substrate to increase its moisture content and 2) applying a bonding agent to the substrate surface. These practices are referred to in ACI 325 as 'pretreatments' (2006). The research conducted as part of this report was performed using three substrate slabs on to which six overlay slabs were bonded. The substrate slabs were mechanically roughened and cleaned, after which the surfaces were prepared with a combination of pretreatments: with or without a bonding agent, and with or without prewetting. Pull-off, direct shear, push off, and slant shear tests were performed to evaluate the effects on bond strength.

1.2 Research Goal and Significance

This thesis seeks to quantify the effect of pretreatments on the shear strength of concrete-to-concrete bondings, including bonded overlays and other types of repairs. The results of the study may be applied to the construction of repairs and to the preparation of the interface between successive concrete placements (cold joints) to develop better strength at the bonded interface.

A variety of different tests were used to measure the effects of pretreatment on bonded strength, including in-place testing and testing performed on extracted samples. Each test measures the strength of the bond in a different way. The results illustrate the sensitivity of each particular test to each pretreatment type, as well as indicate the combination of pretreatments that will best enhance the bond strength over all types of tests.

1.3 Outline

There are six chapters in this thesis. The first chapter introduces the topic and goals of the research.

Chapter 2 is a literature review, summarizing past research into the shear strength of bonded overlays and the effects of pretreatments. The chapter briefly discusses the mechanisms of concrete to concrete bond, and examines the types of tests available to determine bond strength and shear strength.

In *Chapter 3*, the research program is discussed. This includes construction, preparation, and testing of the substrate and overlay slabs. The profiling and cleaning of the substrate surface and the application of the pretreatments is discussed.

In *Chapter 4*, the bond strength and shear strength data is tabulated.

Chapter 5 is a discussion of the experimental results from the four strength tests and the observed effects of the pretreatments.

Chapter 6 presents the conclusions of the research and summarizes future research needs.

The attached appendices include experimental data gathered during the execution of the research program.

CHAPTER II

BACKGROUND

2.1 Introduction

The ability to repair concrete by removing damaged or deteriorated areas and replacing or overlaying them with new concrete has long been understood. Frequently, the goal of repair, whether on a structural member or concrete pavement, is to place the new concrete in such a way that the old and new concrete are able to adequately transfer stresses between one another, such that the member as a whole behaves as if it were made of monolithic concrete. Depending on the loading to which the member is subjected, stresses could act either perpendicular to the interface, causing tension or compression, or parallel with the interface, causing shear. The mechanism resisting these stresses is referred to broadly as bond strength.

The author has compiled existing literature dating from 1919 (Rosengarten) to the present; these studies investigate the means of maximizing bond strength to produce more durable repairs. These studies generally agree that the best bond is obtained using a substrate surface free of laitance (the weak surface layer formed during finishing) and debris. Other recommendations and conclusions can be divided into two categories, as outlined in Table 2.1-1. The first is recommendations regarding surface profiling, which is the intentional roughening of the substrate surface to provide superior mechanical interlock. Much research has examined the effects of bruising, which is the introduction of microfractures into the surface of the substrate during profiling that may weaken the bond strength.

The second category concerns pretreatments, which are substances introduced into the substrate prior to concrete placement to enhance the strength of the bond. This study is primarily concerned with the second category.

Table 2.1-1 – Common examples of surface profiling and pretreatments

Examples of Surface Profiling:	*Examples of Pretreatment:*
Sand/shot blasting	Prewetting/moistening
Impact hammering	Cement bonding agent
Acid etching	Latex bonding agent
Water jetting	Epoxy bonding agent

2.2 Mechanism of Concrete to Concrete Bond

Bond strength is generally measured as either 1) the adhesion or tensile strength of the bond, or 2) the shear strength of the bonded interface. Assuming the bond strength is less than the tensile strength of the concrete, the bond strength will be governed by the failure mode of tensile cracking along the interfacial surface. The failure mode of the bond in shear is more complex, particularly for roughened surfaces. Subjected to shear, mechanical interlock between the two surfaces will contribute to the shear resistance; the failure mode will be a combination of shear and tensile cracking (Austin, S., et al., 1999).

2.3 Methods of Testing Bond Strength

Numerous tests are available to measure bond strength, both in tension and in shear. As Austin, et al. (1999) notes, any one test provides limited information that "taken in isolation, can result in a misunderstanding of the behaviour of bonded cementitious materials". To avoid this bias, the selection of test should ideally involve a stress state to which the repaired member will be subjected to during service (Walls & Shrive, 1988). The test methods selected and discussed herein, as summarized on Table 2.3-1, subject the bonded interface to a variety of stress conditions, including tension, shear, and a combination of compression and shear.

Table 2.3-1 – Summary of common tests for bond strength

Test:	Test Location:	Type:
Pull-off	In-Place	Direct Tension
Guillotine	Laboratory	Direct Shear
Slant Shear	Laboratory	Combination of Compression & Shear
Jacking	In-Place	Direct Shear

2.3.1 Pull off test (ASTM C1583)

The pull-off test is a direct tension test suitable for testing in-place bond strength. The test has been in use in a variety of forms since before 1990 (Hindo, 1990). In 2004, the test was given the designation ASTM C1583 (2015), and it is currently (to the author's knowledge) the most commonly used testing procedure for bond strength. However, its accuracy has been repeatedly called into question, with one study for the U.S. Army Corps of Engineers noting that "results obtained…can be described as variable or very variable" (Vaysburd & McDonald, 1999).

The procedure begins by coring through the overlay and partially into the substrate. Vaysburd and McDonald (1999) found that the depth of the core into the substrate significantly affected the strength results. They recommended a minimum penetration into the substrate of 25 mm (1 in). ASTM C1583, conversely, specifies a minimum depth into the substrate of 10 mm (0.5 in). After the core has been prepared and cleaned, a stainless steel puck is epoxied to the surface of the core and the epoxy is allowed to cure.

Once epoxy curing is complete, the apparatus is placed above the core (Figure 2-1). The specimen is loaded in tension by means of a threaded rod inserted into the top of the steel puck. The ASTM C1583 requires a constant loading rate of 35 ± 15 kPa/s (5 ± 2 psi/s); it has been found that higher rates of loading correspond to higher bond strength results (Vaysburd & McDonald, 1999). The test must be performed with the apparatus set as near perpendicular to the bonding surface as is practical to minimize unintended eccentricity in the applied load.

Figure 2-1 – Example pull-off test (ASTM C1583) apparatus

The test may result in one of several possible failure mechanisms. The partial core may fail entirely above or below the bonded surface, indicating that the strength of bond exceeds the tensile strength of the new or old concrete. Clearly, the observed result in such case represents the tensile strength of the failed concrete and does not represent a bond strength. Another possible mode consists of failure of the epoxy which secures the stainless steel puck to the overlay surface.

These failure modes indicate only that the bond strength exceeds the test result; they do not provide an actual value for bond strength. The pull off test will provide a representative bond strength only when failure occurs at or very near to the bond surface. For this reason, ASTM C1583 cautions that results may be averaged together only if they exhibit the same failure mode.

The pull-off test measures adhesion at the bonded surface, which is typically considerably lower than the shear strength of the bonded interface. A factor is required to convert the value determined with the pull-off apparatus to a value for shear strength. Rosen (2016), referencing a 2000 study by Delatte, et al., multiplied the measured pull-off strengths by 2.04 to estimate shear strength.

2.3.2 Direct shear (guillotine) test

Although there is no ASTM standard for the direct shear test, several are known to be in use in locations throughout the United States. This test is similar to an "Iowa-type shear test" after Iowa Test Method 406-C (2000), which is referenced in ACI 325-06. It is also similar to a "Brookhaven National Laboratory guillotine shear test" (Illinois Bureau of Materials and Physical Research, 2012). It differs from the aforementioned, single shear tests in that the shearing action is applied at two locations (double shear) on the sample: the first is at the bonded interface where failure will occur, and the second is about 76 mm (3 in) away from the interface and is present only to stabilize the specimen during testing. The apparatus is pictured in Figure 2-2 and its usage is described in detail, below:

Figure 2-2 – Direct shear test in-progress

The test apparatus consists of a set of nested boxes, called a guillotine. Full depth core samples are taken perpendicular to the bond surface and transferred to the laboratory. After drying, the cores are placed in the guillotine with the bond plane centered between the edges of the nested boxes. The apparatus is compressed, which induces shear on the bond plane until failure occurs. Test 406-C recommends a loading rate in the range of 45 to 60 kPa/s (400 to 500 psi/min).

2.3.3 Slant shear test

Slant shear tests are commonly used by manufacturers for testing the performance of proprietary bonding agents (Austin, S., et al., 1999); this test has been formally adopted as ASTM C882: "Standard Test Method for Bond Strength of Epoxy-Resin Systems used with Concrete in Shear". This test was first known as the Arizona Slant Shear test (Austin, S., et al., 1999) (Kriegh, 1976). In a typical laboratory testing scenario, concrete is placed in a cylinder mold with a plate installed that forms the interior face at a 60-degree angle. The plate is removed once the concrete has cured, and the bonding surface is prepared as desired before casting the 'overlay' concrete in the mold. The resulting specimen is then compressed to its ultimate strength (Figure 2-3).

Figure 2-3 – Preparing to test slant shear sample on compression machine. Note difference in concrete color indicating the slanting bond surface

Multiple studies conclude that slant shear tests are among the most sensitive to the type and proportions of the materials used to create the bond surface Kriegh (1976). However, the test is also extremely sensitive to the roughness or profiling of the substrate. Austin, et al. (1999) obtained bond failure solely with specimens prepared with relatively smooth substrates. In his research, he noted that several roughened specimens failed in compression instead of shear failure at the bonded surface. However, other researchers, such as Rosen (2016), have obtained good results for roughened surfaces.

The slant shear test exerts a combination of compression and shear on the bonded surface resulting from the angle of inclination of the surface. The compression force can be resolved into two components: a compression stress 'σ_N' normal to the bond surface, known as clamping force, and shearing stress 'τ_{NT}' parallel to the bond surface (Figure 2-4).

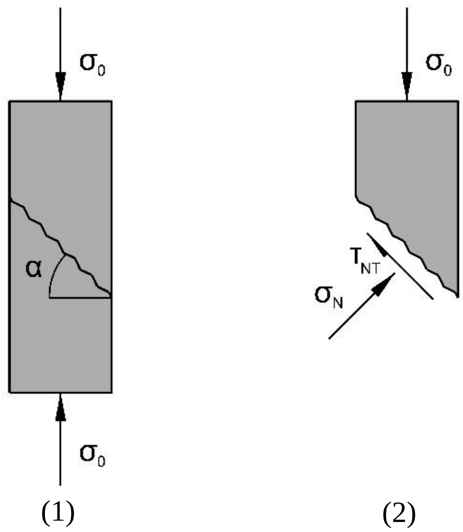


Figure 2-4 – Diagram showing (1) the slant shear specimen under uniaxial compression stress and (2) the resulting stresses on the bond surface

Appendix E contains additional information related to the slant shear test, including a discussion of the effect of slant angle 'α' on the transformed stresses.

2.3.4 Jacking test

The jacking test is a direct shear test used for in place testing. The procedure involves sawcutting the overlay into smaller block specimens. A hydraulic jack is installed adjacent to the blocks and is secured to the substrate. Ideally, the jack should be oriented such that the shearing force is applied as closely as possible to the surface of the substrate, so as to minimize the overturning moment component of the force (Rosen, 2016). A steel plate can be inserted between the ram and the block to distribute the shearing force evenly across the face of the block. Shear is applied (Figure 2-5) until the sample fails, and the maximum applied force is recorded.

2.4 Pretreatments

Pretreatments, as the name implies, are basic additions to the smooth or profiled substrate intended to increase the strength and durability of the concrete-to-concrete bond. The addition of water into the otherwise dry substrate is referred to as “prewetting”. The cementitious material added to the surface of the substrate prior to concrete placement is referred to as a bonding agent. Both treatments have been in common use for over a century. Paragraphs, below, describe the intended benefit of pretreatments.

Figure 2-5 – Block specimen undergoing jacking test

2.4.1 Prewetting

The surface of a dry substrate, particularly one that has been made more porous by the removal of laitance during profiling, has a relatively high moisture demand. The effect of prewetting the substrate concrete fills the existing capillaries that would otherwise tend to draw water out of the new overlay concrete. This may result in a condition wherein not enough free water is present to fully hydrate the overlay cement; this may reduce concrete strength at the interface. The term Saturated Surface Dry (SSD) is often used to describe a condition where the continual wetting of the substrate in the period leading up to an overlay fills the pores of the old concrete. The surface is allowed to dry prior to placement so as not to weaken the new concrete by increasing the water/cement ratio at the bond interface.

2.4.2 Bonding agents

The earliest bonding agents in common use consisted of a cement-water slurry (cement-neat) or a cement-sand-water slurry. These agents are still commonly specified as a means to achieve a more durable bond. Other bonding agent products, such as latex-modified grout or epoxy grout, have been introduced more recently. In any case, the agent is typically scrubbed into the surface of the substrate immediately before overlay concrete is placed.

The mechanism by which a bonding agent enhances concrete-to-concrete bond is not entirely clear. It may be that the action of scrubbing the agent into the substrate coats assimilates dust particles that were not removed by cleaning (Silfwerbrand & Paulsson, 1998).

2.5 Literature Review

Existing studies containing conclusions or recommendations regarding pretreatments were identified during the literature review phase. The execution and results of these studies are described in chronological order in the paragraphs below. Codified recommendations regarding pretreatments are also discussed. The summary section tabulates and compares nearly a century of research into pretreatments.

2.5.1 Early studies

In 1919, W. E. Rosengarten, a researcher with the Bureau of Public Roads (a forerunner of the Federal Highway Administration (FHWA)), published his findings on the strength of concrete-to-concrete bondings. Though concrete pavement had been used as early as 1896 in the United States (Pasko, 1997), it was not in common use until after 1910. When Rosengarten conducted his research, concrete pavement was entering a decade of service and much of it likely needed rehabilitation. Rosengarten prepared some of his specimens using a bonding agent, which he termed a “cement butter layer” (Rosengarten, 1919). He also wet the substrate of some of his samples prior to bonding the overlay. The impact on the strength of the bond was evaluated using both direct tension and direct shear tests, as well as a flexure test. Rosengarten found that the bonding agent added 25 percent to the tensile strength of the bond, and also benefited the strength in shear. His results on prewetting, which he notes was common practice at the time, were inconclusive for tension. Rosengarten did see an increase in shear strength due to prewetting.

In 1956, Felt conducted his now widely cited research with the goal of identifying the factors which maximized the shear strength, and therefore the durability, of an overlay (Felt, 1956). Along with other variables, Felt investigated the effects of prewetting and the use of bonding agent. He began by evaluating small (240 x 240 x 84 mm) (9.5 x 9.5 x 7 in) bonded prisms to guide his selection of pretreatments for the remainder of the study. He followed this with much larger (400 x 1020 x 84 mm) (16 x 40 x 7 in) slabs, some of which were laboratory cast, and others in which the substrate was cut from pavement that had been in service for several decades. Felt tested his samples using a single shear, guillotine-type apparatus. He concluded that a "dry" substrate was preferable to "damp" and that a cement or cement-sand slurry bonding agent produced a superior bond. Noting the amount of scatter in his data, Felt wrote "…it became apparent that factors influencing bond of new and old concrete were not easily isolated and controlled". This sentiment has been echoed by many contemporary researchers. The difficulty in isolating the variables that have the principle effect on bond strength may explain the conflicting conclusions of the more modern literature, discussed below.

2.5.2 Modern studies

Wall and Shrive (1988) conducted a study that included finite element modeling of an interfacial bond, in conjunction with laboratory experimentation on 112 prismatic samples using a combined shear/compression test. Their FEM model indicated that consistency of the bonding agent was critical; a void in the bonding material was found to significantly increase the stress in the adjacent areas of the bond material. Based on laboratory experimentation, they found that superior bond strength can be achieved with or without a bonding agent; however, their results indicate less scatter in the data when a bonding agent was employed, an effect first noted by Felt. In disagreement with Felt's findings, Wall and Shrive observed an improvement in strength due to prewetting of the substrate.

In 1991, Saucier and Pigeon presented the results of a study based on the results of combined shear/compression tests on over 2,000 bonded concrete prisms. The prisms themselves were relatively small cubes with dimensions of 75 x 75 x 75 mm (3 x 3 x 3 in) and were used in conjunction with a coarse aggregate size of 12 mm (0.5 in) (Saucier & Pigeon, 1991). The study results generally agreed with Felt's conclusions: the use of a bonding agent will increase the strength of the bond, and prewetting the substrate does not improve bond strength. Saucier and Pigeon also experimented with allowing some drying of the bonding agent. Felt had recommended that the bonding agent be allowed to dry slightly on the substrate before placement of the overlay, stating: "grout that has lost its water sheen is in proper condition for the concreting operation" (Felt, 1956). Saucier and Pigeon allowed the bonding agent to dry for 45 minutes on some of their specimens prior to placing the overlay. They noted the dried agent caused a slight increase in bond strength when applied to an SSD substrate, but caused a decrease in bond strength when applied to a dry substrate.

In a large test involving over 150 substrate slabs with dimensions of 915 x 915 x 130 mm (36 x 36 x 5 in), Whitney, et al. (1992) found that the majority of debonding between substrate and overlay occurs during the early curing of the overlay. The study found that good bond strength could be achieved through the application of epoxy bonding agents, particularly in harsh environmental conditions. They noted that the application rate of the bonding agent did not seem to greatly affect the strength of the bond. The study also found that both high substrate surface temperatures before placement, and large changes in ambient temperature in the 24 hours following an overlay, adversely affected the measured bond strength.

In a 1998 article focusing on the rehabilitation of bridge decks in Sweden, Silfwerbrand and Paulsson advised against the use of bonding agents. They note that the use of a bonding agent creates two possible planes of weakness between the overlay and substrate (Silfwerbrand & Paulsson, 1998).

Wells and Stark found that substrate surfaces prepared by shotblasting produced consistently good bond strengths without the need for a bonding agent. However, they did find that bonding agents did have a positive effect on slabs prepared using other surface profiling methods (Wells & Stark, 1999).

Djazmati and Pincheria (2004) conducted a study on the effects of surface profiling and pretreatment at the interfacial bond between successive concrete placements (cold joints). In contrast to much of the literature on this topic, Djazmati and Pincheria examined bonding to recently placed substrate (as little as 24 hours old) to simulate cold joints formed during construction. They found that a joint that had been saturated with water was about half as strong as a dry joint. They recommended moist curing the joint for a minimum of 24 hours prior to placement, but cautioned that the joint surface should appear dry before commencing with the second placement. Djazmati and Pincheria also studied the effect of a resin emulsion bonding agent on a smooth joint. They found that the resin emulsion bonding agent, being substantially less stiff than concrete, caused the resulting joint to be much more flexible than monolithic concrete. Therefore, they recommend against the use of a resin emulsion bonding agent at cold joints.

In a report for the Bureau of Reclamation, Bissonnette, et al. (2012) concluded that moistening of the substrate is beneficial, and that optimum saturation in the substrate surface lies somewhere between 55 and 90 percent, though he states that “fundamental issues remain unsolved with regard to moisture conditioning of the concrete substrate…”. Bissonnette recommended against the use of bonding agents for reasons similar to those expressed by Silfwerbrand and Paulsson (1990).

Julio, Branco, and Silva (2004) concluded that pre-wetting the substrate does not significantly influence the bond strength.

2.5.3 Code references

Both ACI 325 (2006) and ACI 345 (2011) express concern over the effectiveness of bonding agents and the potential for debonding if the bonding agent is improperly applied. The Portland Cement Association (1996) recommends a thin coat of “bonding grout” consisting of a cement-sand slurry be scrubbed into the substrate surface prior to placement of bonded overlays. Meanwhile, the National Concrete Pavement Technology Center states that bonding agents are not required for concrete-to-concrete pavement overlays (Harrington, 2008).

2.5.4 Previous research at the University of Colorado – Denver

This study builds on the findings of a previous program of research performed at the University of Colorado – Denver by Christian Rosen (2016). Rosen's work involved testing the effects of various substrate surface profiles, ranging from rough to smooth, on the shear strength of bonded overlays. He found that surface roughness had a significant effect on shear strength, with the roughest surface preparation producing the highest strengths. Rosen also examined the effects of the compaction of concrete on interfacial shear strength; he found that proper compaction of the overlay significantly increased shear strength.

2.5.5 Summary of literature review

It is apparent when reviewing the literature that the effectiveness of pretreatments remains the subject of debate. Table 2.5-1 summarizes the findings of twelve previously cited studies with regards to pretreatments. It should be acknowledged that this table greatly simplifies the results and conclusions of these studies for the purposes of comparison. Immediately obvious when reviewing this table is the lack of any clear trends that might tend to guide the practicing engineer. As Talbot, et al. (1994) remarks: "the conclusions obtained by various investigators are unfortunately often influenced by the specific type of testing procedure used". Environmental factors, such as humidity, ambient temperature, and rate of evaporation may significantly affect the need for prewetting. The degree of preparation of the substrate, including profiling and cleaning, may determine the effectiveness of a bonding agent. These factors are not easily controlled and are often difficult to measure, even in a laboratory environment.

Table 2.5-1 – Summary of results regarding pretreatments

Year of Article/Report	Author	Results Regarding Pretreatments: ('+': increase in strength/durability, '–': decrease in strength/durability, '+/–': inconclusive)	
		Prewetting	Bonding Agent
1919	Rosengarten	+/–	+
1956	Felt	–	+
1988	Wall and Shrive	+	+/–
1991	Saucier and Pigeon	–	+
1992	Whitney, et al.	N/A	+
1998	Silfwerbrand and Paulsson	N/A	–
1999	Wells and Stark	N/A	+/–
2004	Djazmati and Pincheria	+/–	–
2004	Julio, Branco, and Silva	+/–	N/A
2006	ACI 325	+/–	+/–
2011	ACI 345	+	+/–
2012	Bissonnette, et al.	+	–

CHAPTER III

RESEARCH PROGRAM

3.1 Construction of Substrate and Overlay Slabs

The research program evaluated the bond strength of concrete overlays using 6 different combinations of pretreatments. In total, three substrate (138 x 147 x 8.3 cm) (54 x 56 x 3¼ in) (Figure 3-1) and six overlay (91 x 61 x 8.9 cm) (36 x 24 x 3½ in) slabs were cast using a commercially available sack concrete mix with a design 28-day strength of 34.5 MPa (5,000 psi). The maximum coarse aggregate size for the sack concrete was 9.5 mm (3/8 in). The design slump was approximately 76 mm (3.0 in). Approximately 0.62 cubic meters (22 cubic feet) and 0.28 cubic meters (10 cubic feet) of concrete was placed for the substrate and overlay slabs, respectively. The concrete was mixed in small, ±0.08 cubic meter (3 cubic foot) batches. Seven batches were necessary to construct the substrates; six were needed to construct the overlays.

Figure 3-1 – Typical substrate form, ready to receive concrete

The substrate slabs were cast outdoors and covered with a tarp for the initial curing period. Cylinders, taken during concrete placement, were tested for compressive strength at 3, 7 and 28 days to establish the maturity curve for the mix. The average 28-day compressive strength for the substrate was 41.5 MPa (6,010 psi), with a relatively low standard deviation of 1.9 MPa (269 psi). The average 28-day compressive strength for the overlay was 38.3 MPa (5,558 psi), with a standard deviation of

9.10 MPa (1320 psi). All slabs were compacted with an immersion vibrator during placement; proper vibration has been shown to increase the shear strength at the bonded interface (Rosen, 2016). Both the substrate and the overlay slabs were unreinforced with the exception of #3 hairpin bars placed as anchor reinforcement for the bolts used in the jacking test. The hairpins were located entirely within the substrate slab with approximately 1 in (25 mm) clear coverage to the surface of the substrate.

It was decided that overlay placement would occur no sooner than 28 days following the placement of the substrate. This wait was imposed to allow the substrate 1) to gain strength such that the possibility of fracturing during surface profiling was minimized, and 2) to accomplish initial shrinkage prior to the placement of the overlay, to best simulate the differential shrinkage that typically occurs when an overlay is placed on existing concrete. Surface preparation commenced exactly 28 days following the substrate placement. Laitance was removed by means of a bush hammer attachment on a small, handheld demolition hammer (Figure 3-2). As shown in Figure 3-3, the prepared surface roughness was similar to Concrete Surface Profile 6 (CSP 6), medium scarification, as depicted in ICRI Guideline No. 310.2R (International Concrete Repair Institute, 2013). The surfaces were then thoroughly cleaned using compressed air followed by vacuuming.

Figure 3-2 – Surface profiling the substrate

Figure 3-3 – Finished profile compared with ICRI CSP 6 example.

Following surface profiling and cleaning, the six bonding surfaces received different pretreatments, identified in Table 3.1-1.

Table 3.1-1 – Pretreatment summary

Overlay Slab No.:	Moisture Condition of Substrate:	Bonding Agent:
1A	Dry	None
1B	Dry	Wet Cement Slurry
2A	SSD	Wet Cement Slurry
2B	SSD	Dried Cement Slurry
3A	Saturated with standing puddles	Wet Cement Slurry
3B	SSD	None

Note: SSD = "Saturated Surface Dry"

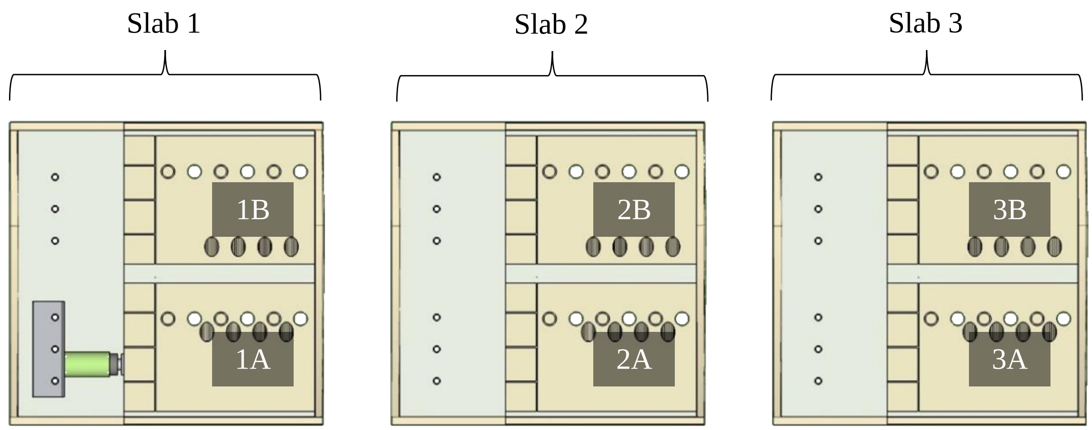
"Dry" substrate slabs were not permitted to come into contact with water for several days prior to placement of the overlay. Saturated Surface Dry (SSD) slabs (Figure 3-4) were repeatedly moistened for a period of about one hour, then any standing or free water on the surface was allowed to evaporate prior to overlay placement. As the name implies, SSD refers to a condition wherein the pores of the existing concrete are filled with water, but excess moisture on the concrete surface has evaporated Slab 3A was initially prepared similarly to the SSD slabs, but puddles of standing water were allowed to remain on the surface during overlay placement. All these surface conditions were intended to envelope possible field conditions.

Figure 3-4 – Example of saturated, surface dry appearance immediately before placement

Figure 3-5 – Application of cement slurry bonding agent

The selected bonding agent was a cement and water slurry with a w/c ratio of 0.50. Previous research, including research referenced in ACI 325 (2006) and Saucier and Pigeon (1991), indicates that a bonding agent with a w/c ratio in excess of 0.60 could significantly weaken the bond. The bonding agent was scrubbed into the substrate with a stiff bristle brush (Figure 3-5) as recommended by Wells and Stark (1999). In all but one case, the overlay was placed on the bonding agent immediately, prior to any drying or dulling of the slurry. In the case of Slab 2B, the slurry was allowed to sit for a period of several days, such that it was fully dry at the time of overlay placement. As a means of reducing the amount of formwork needed, two overlay slabs were placed on a common substrate slab. The bleed-over of moisture during pretreatment from the adjacent bonding surface was considered in the experiment layout. Pretreatments involving dry substrates were grouped together on Slab 1, while SSD or wet substrates were grouped together on Slab 2 and Slab 3.

Slabs 1A, 1B, 2A, and 3A were placed when the substrate was 30 days old. A sudden rainstorm prevented the completion of the remaining overlays, which were placed five days later (substrate age of 35 days). The overlays slabs were formed from the same concrete mix as the substrate, but were treated with a commercially available colorant to help in the identification of the bonding surface. An overall plan showing the relative arrangement of the substrate and overlay pads is presented in Figure 3-6. An isometric view of a typical substrate slab and two overlay pads is presented in Figure 3-7. This figure shows the typical slab dimensions and the approximate locations where the various test samples were taken. The testing is discussed in detail in Chapter 3.2. Figure 3-8 and Figure 3-9 illustrate the as-constructed condition of the slabs.



Slab 1A:
Dry Substrate/No Bonding Agent

Slab 1B:
Dry Substrate/Wet Bonding Agent

Slab 2A:
SSD Substrate/Wet Bonding Agent

Slab 2B:
SSD Substrate/
Dried Bonding Agent

Slab 3A:
Wet Substrate/Wet Bonding Agent

Slab 3B:
SSD Substrate/No Bonding Agent

Figure 3-6 – Plan view of slabs and pretreatments

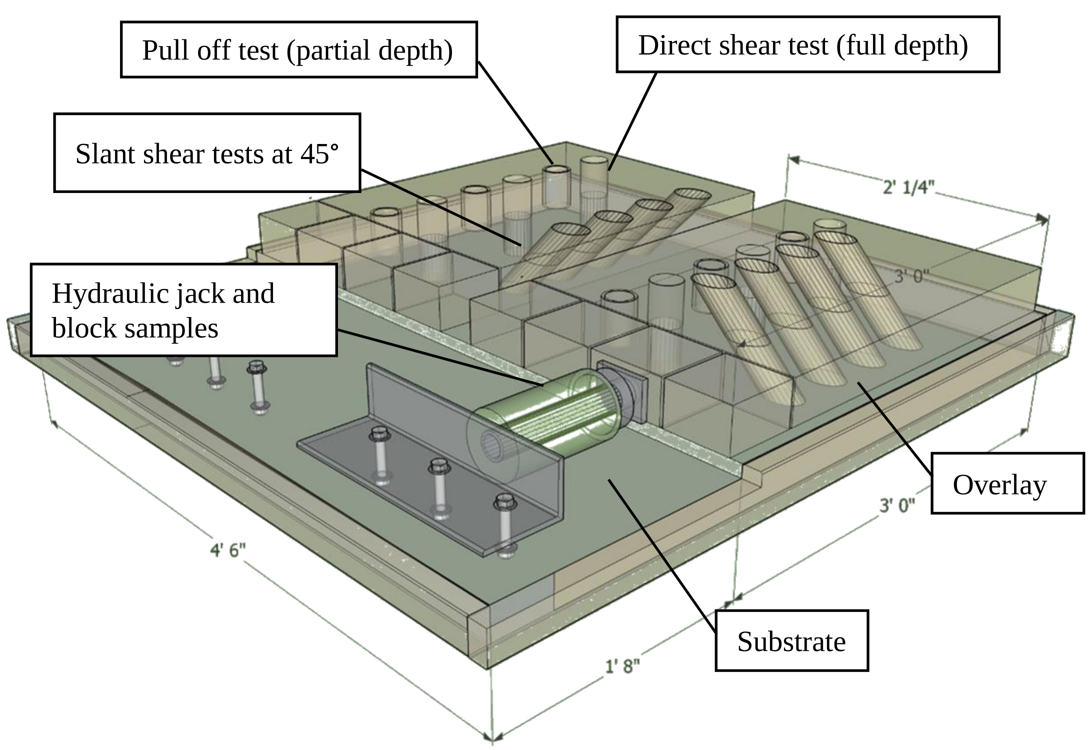


Figure 3-7 – Isometric rendering of a typical substrate slab with two overlay slabs

Figure 3-8 – As constructed view showing pull-off test sampling locations.

Figure 3-9 – As constructed view showing pull-off, direct shear, slant shear, and jacking test sampling locations. Background to foreground: Slab 1, 2, and 3

3.2 Testing

All testing was performed in the Civil Engineering Laboratory at the University of Colorado – Denver. Testing of the compressive strength of the substrate and overlay concrete was accomplished between 3 and 28 days after placement of the concrete. Testing of the bond strength was conducted in the order shown on Table 3.2-1. The pull off tests were conducted 40 days after the final overlay slab was constructed. Direct shear tests were conducted next, 65 days after the final overlay slab was constructed. Slant shear tests and jacking tests were conducted 80 and 90 days after the final overlay slab was constructed, respectively.

Table 3.2-1 –Testing Summary

Test:	Test Location:	Type:	No. of Samples Tested:	Standard (if applicable):
Compression	Laboratory	Compression	3 per batch (36 total)	ASTM C39
Pull-off	In-Place	Direct Tension	3 per slab (18 total)	ASTM C1583
Direct Shear (Guillotine)	Laboratory	Direct Shear	3 per slab (18 total)	N/A
Slant Shear	Laboratory	Combination of Compression & Shear	4 per slab (24 total)	ASTM C882
Jacking	In-Place	Direct Shear	4 per slab (24 total)	N/A
Total			**120 tests**	

3.2.1 Slump test

Slump was measured using a standard slump cone (Figure 3-10) test and was conducted for seven of the thirteen concrete batches. The design slump for the sack concrete product used in the testing program is 50 – 76 mm (2 – 3 in). Slump results are tabulated in Section 4.1.

Figure 3-10 – Example slump cone test on overlay concrete (note integral color)

3.2.2 Slab concrete compression test

Samples were taken during placement of the substrate and overlay slabs in 102 (diameter) x 203 mm (4 ϕ x 8 in) plastic cylinder molds. Three samples were taken from twelve of the thirteen total batches for a total of 36 specimens. A single cylinder from each batch was tested in compression at 3-, 7-, and 28-days after placement. Testing was performed on a Forney compression testing machine (Figure 3-11) equipped with an Admet data logger. The cylinders were capped prior to testing with reusable neoprene rubber pads surrounded by a steel extrusion controller. The Forney machine was not equipped with a displacement sensor, therefore, only the compression load at failure was recorded. Load rate was controlled using a hand wheel and was adjusted so as to maintain the rate prescribed in ASTM C39 (2004) of 0.25 ± 0.05 MPa/s (35 ± 7psi/s). For a 4 in (102 mm) standard cylinder, the rate of load application is 440 ± 88 lbs/s. Compression stress at failure was determined from the applied load at failure using Equation (3-1). Results from the compression strength tests can be found in Chapter 4.2.

$$\sigma = \frac{P_u}{A_g} \quad (3\text{-}1)$$

Where: σ = compressive strength (MPa or psi)

P_u = compressive force at failure (kN or lbs)

A_g = gross area of the sample (mm^2 or in^2)

Figure 3-11 – Compression Testing Equipment

3.2.3 Pull-off test

Samples were prepared using a 66.7 mm (2 5/8 in) inner diameter coring bit with a 406 mm (16 in) coring depth capacity mounted on a wet core drill. A guide was placed on the bit such that the core would penetrate approximately 1.3 cm (0.5 in) into the substrate slab. The cores were taken as close to perpendicular to the bond plane as possible to minimize the eccentricity of the applied test load. Once coring was completed, the annular space was rinsed thoroughly with water to remove dust and debris. The surface of the overlay at the core location was treated with full-strength Muratic acid to remove laitance, then thoroughly rinsed with water. After waiting for the surface to dry, any remaining dust was blown off with compressed air (Figure 3-12). 76.2 mm (3 in) diameter stainless steel pucks were epoxied onto the top of the partial cores and the epoxy was left to cure for a period of several days.

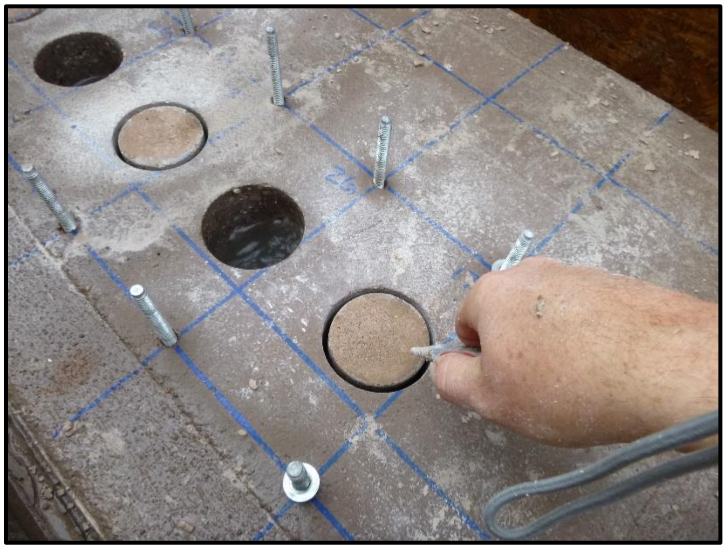


Figure 3-12 – Cleaning the surface of the pull-off test specimen

Tensile strength of the bond was tested using Non Destructive Testing Systems (NDT) 007 James Bond Tester furnished by CTL-Thompson (Figure 3-13). The location of the failure plane and the maximum tensile force was recorded for each test.

Figure 3-13 – NDT 007 James Bond Tester

In accordance with the testing frequency recommendations of Part 8 (Sampling) of ASTM C1583, three tests were performed on each of the six overlay slabs. In 13 of the 18 tests, failure occurred at the bond line. The remaining tests failed on the surface of the substrate. Several tests were aborted due to failure of the epoxy bonding the stainless steel puck to the overlay. In these cases, the puck was rebonded to the specimen and the test was resumed at a later date.

The bond strength is calculated from the maximum tensile load using Equation (3-2); the relationship is similar to that used in the compression test. Results from the pull-off tests can be found in Chapter 4.5.

$$\sigma = \frac{P_u}{A_g} \tag{3-2}$$

Where: σ = bond strength (kPa or psi)

P_u = tensile force at failure (kN or lbs)

A_g = gross area of the specimen (mm^2 or in^2)

3.2.4 Direct shear (guillotine) test

A guillotine box apparatus was furnished by CTL-Thompson, Inc. Full depth core samples were taken using a 66.7 mm (2 5/8 in) inner diameter coring bit mounted to a wet core drill. The specimens were placed in the guillotine with the bond plane centered between the edges of the nested boxes (Figure 3-15) such that approximately 3.2 mm (1/8 in) of gap was observed between the inner and outer box walls. The apparatus was compressed, which induced shear on the bond plane until failure occurred. The testing was performed using an 89.0 kN (20,000 lbs) MTS compression testing machine with displacement control (Figure 3-14). The loading rate was set at 0.5 mm/min (0.02 in/min). The shear strength at the bonded interface is calculated from the applied force in Equation (3-3). Dividing the applied load by two is necessary because the shearing action is imposed equally on each leg of the box, though failure was found to occur only on the bonded interface.

Figure 3-14 – MTS testing equipment with direct shear apparatus

It may be argued that the eccentricity in applied load resulting from the gap between the inner and outer walls of the guillotine box induces a bending moment on the specimen (and thus the bonded interface is not in pure shear). While the influence of moment is not easily avoidable, the construction of the apparatus with the narrow gap between boxes minimizes the effect.

$$\tau = \frac{P_u}{2\ A_g} \qquad (3\text{-}3)$$

Where: τ = shear strength at bonded interface (kPa or psi)

P_u = compressive load at failure (kN or lbs)

A_g = gross area of the specimen (mm^2 or in^2)

Although each leg of the box is profiled so as to cradle the specimen uniformly, in practice it was observed that some localized crushing of concrete during the early stages of loading was necessary to “seat” the sample. Once this crushing occurred, the stress-strain plot indicates a relatively linear relationship until failure occurs. The author understands that cast plaster caps around the sample and guillotine apparatus are sometimes used to fill the annular space, such that the loading is applied more uniformly. While the benefits of this approach are undeniable, it is difficult to implement capping when testing a large number of samples due to the time involved. For these experiments, the samples were not capped.

Results from the direct shear tests can be found in Chapter 4.6.

Figure 3-15 – Direct Shear (Guillotine) Apparatus

3.2.5 Slant shear test

As noted in Chapter 2.3.3, slant shear specimens are typically prepared using a cylindrical mold with a removable plate to form the slanted interface. Although this is a convenient method to produce many specimens, it was not the preferred method for this study. For this study, it was decided that slant shear specimens would be cored directly from the slabs, such that the surface profiling and pretreatment would be identical across all four types of tests. This necessitated coring samples on an angle, and then sawing the ends perpendicular to the axis of the core. Figure 3-16 defines how the slant angle 'α' was measured in this study.

Full depth core samples were taken at 45 degrees from normal (Figure 3-17) using a 66.7 mm (2 5/8 in) inner diameter coring bit mounted to a wet core drill. The slant angle was selected based on: 1) the maximum slant capability of the core drill stand used in the experimentation, and 2) the ability to obtain more samples than would have been possible had cores been attempted at a shallower angle (due to space limitations). The ends of the samples were sawed perpendicular, and then allowed to dry for a minimum of 5 days in accordance with ASTM C42 (2004). The samples were then compressed to failure on a 1000 kN (220,000 lbs) MTS compression testing machine with displacement control. The loading rate was set at 0.10 mm/min (0.04 in/minute).

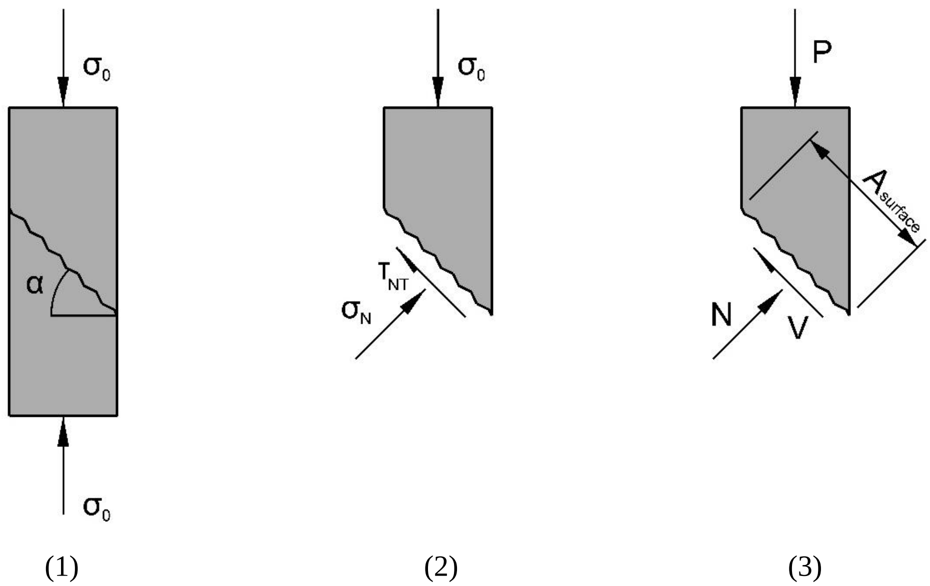


Figure 3-16 – Diagram showing (1) the slant shear specimen with slant angle 'α' subjected to uniaxial compression, (2) the stresses on the bond surface, and (3) the forces on the bond surface

Figure 3-17 – Checking the slant angle with an inclinometer prior to coring for a slant shear specimen

The principle stresses at the bonded interface were determined using a 2-dimensional plane stress transformation. The normal or clamping stress is given by Equation (3-4), while the shearing stress at the interface is given by Equation (3-5). These variables are depicted in Figure 3-16.

$$\sigma_N = \frac{P_u/A_g}{2}\left(1 + cos(2\alpha)\right) \quad (3\text{-}4)$$

$$\tau_{NT} = \frac{P_u/A_g}{2}(sin(2\alpha)) \quad (3\text{-}5)$$

Where: σ_N = clamping force at failure (kPa or psi)

τ_{NT} = shear stress at failure (kPa or psi)

P_u = compressive load at failure (kN or lbs)

A_g = gross area of the specimen (mm^2 or in^2)

α = slant angle (degrees from horizontal)

This relationship can also be expressed in terms of forces acting on the bond surface $A_{surface}$. Equation (3-6) gives the normal stress in terms of the clamping force, while Equation (3-7) gives the shearing stress in terms of the shear force.

$$\sigma_N = \frac{N}{A_{surface}} \quad (3\text{-}6)$$

$$\tau_{NT} = \frac{V}{A_{surface}} \quad (3\text{-}7)$$

Where: σ_N = clamping force at failure (kPa or psi)

τ_{NT} = shear stress at failure (kPa or psi)

N = clamping force on bonded interface (kN or lbs)

V = shear force at bonded interface (kN or lbs)

$A_{surface}$ = area of bonded interface (mm^2 or in^2)

This transformation can also be expressed graphically using Mohr's circle of stress, as shown in Figure 3-18. Under uniaxial stress, one quadrant of Mohr's circle passes through the origin, while the other quadrant is located at the maximum principle stress. The figure illustrates the computation of the normal and shear stresses on a 45 degree and 60 degree slant, under a hypothetical uniaxial compressive stress of 1.0 ksi (0.145 MPa). At 45 degrees, the normal and shear stresses are equal. At 60 degrees, the normal stress is significantly reduced. Refer to Appendix E for a discussion of how the effect of friction significantly affects the observed shear resistance at the bonded interface.

Of the 24 slant shear specimens tested, none were found to have failed in shear at the bonded interface as anticipated. All samples failed in splitting tension in a manner similar to typical compressive cylinder tests. Figure 3-19 and Figure 3-20 illustrate the typical failure condition observed. It appears that the clamping force on the roughened bond plane was sufficient to resist the applied shear force on the 45 degree bond plane.

Results from the slant shear tests can be found in Chapter 4.7.

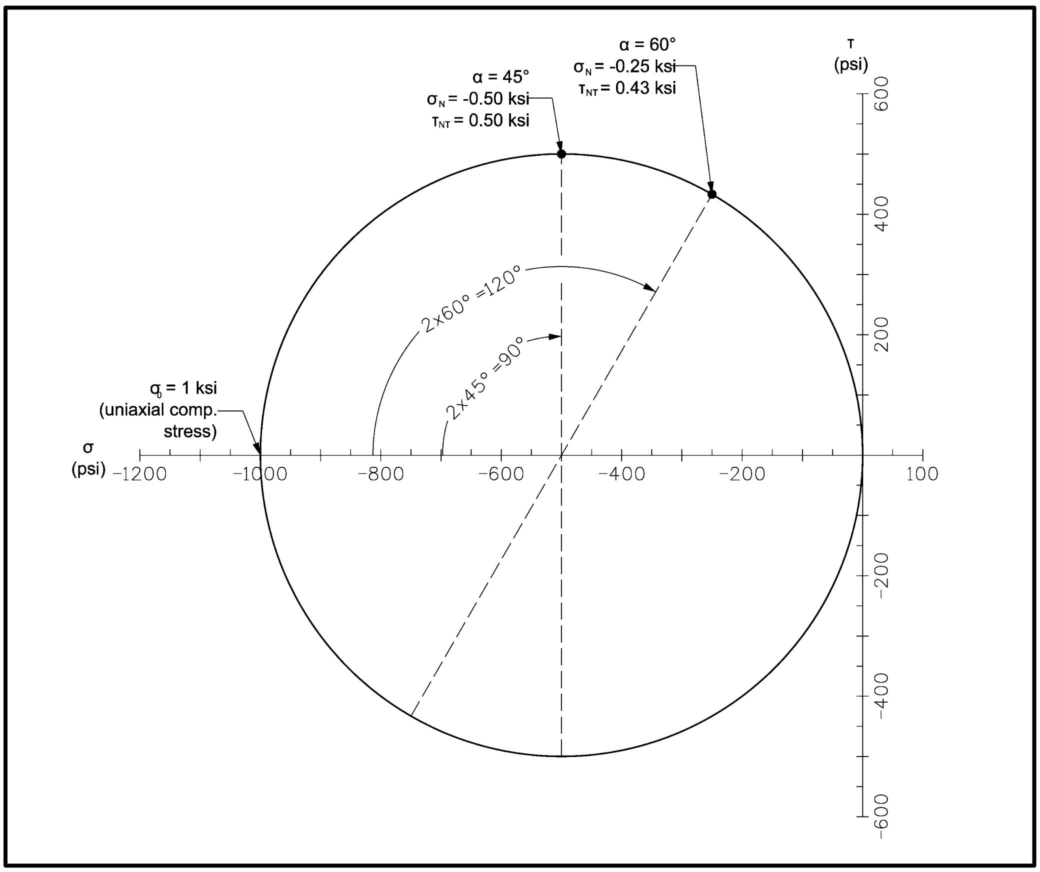


Figure 3-18 – Mohr's circle under 1 ksi (0.145 MPa) uniaxial compression at slant angles of 45 and 60 degrees (Sign convention for σ: + tension / - compression) (Sign convention for τ: + CW / - CCW rotation)

Figure 3-19 – Representative slant shear cylinder after testing under uniaxial compression

Figure 3-20 – Same specimen as Figure 3-19, opened to reveal surface of splitting tension failure. Note colored concrete is overlay; gray concrete is substrate

3.2.6 Jacking test

Sample blocks were prepared using a 350 mm (14 in) dry concrete saw with an adjustable shoe to set the depth of cut (Figure 3-21). The saw was connected to a wet/dry vacuum to minimize the dust generated by this operation. The blocks were cut to a preferred size of 152 x 152 mm (6 x 6 in) where possible; however, clearance between the test slabs and an adjacent wall necessitated adjusting the block dimensions for some of the ‘A’ slabs. The saw was adjusted such that the depth of the sawcut extended approximately 13 mm (0.5 in) into the substrate slab.

Figure 3-21 – Concrete saw and dust collection system

A Simplex RC306C hydraulic jack with a 300 kN (30 ton) capacity was installed adjacent to the blocks. During casting of the substrate, a 25 mm (1.0 in) step had been formed into the surface to accommodate the jack body. This allowed the piston to exert load on the block as close to the bond surface as possible, thereby minimizing overturning moment resulting from eccentric application of the load. A steel plate with dimensions of 89 x 89 x 25 mm (3 ½ x 3 ½ x 1 in) was placed between the piston and the block to evenly distribute the test load.

Figure 3-22 – Simplex RC306C hydraulic testing specimen on Slab 2A. On right, 1 in (25 mm) steel plate; on left, brace angle bolted to substrate

The samples were tested to failure and the maximum force in the jack was recorded. The dimensions of the blocks were recorded by measuring the dimensions of the bonded interface after failure, for increased accuracy. The shear stress at the bonded interface is given by Equation (3-8).

$$\tau = \frac{p_u \times A_c}{L \times W} \tag{3-8}$$

Where: τ = shear stress at failure (kN or lbs)

p_u = recorded pressure in jack at failure (kPa or psi)

A_c = area of the jack cylinder; 4,150 mm^2 (6.44 in^2) for the Simplex RC306C

L = length of the block specimen (mm or in)

W = width of the block specimen (mm or in)

CHAPTER IV

RESULTS

4.1 Slump Cone Results

Slump was tested for 7 of the 13 total concrete batches used in the test program. Table 4.1-1 lists the measured slump (a blank entry indicates no measurement was taken).

Table 4.1-1 – Results of slump cone test

Batch No.	*Slab ID*	*Slump*	
		mm	*in*
Substrate Placement (April 7, 2016)			
1	Substrate Slab 1	76	3.00
2	Substrate Slab 1	95	3.75
3	Substrate Slab 2	102	4.00
4	Substrate Slab 2		
5	Substrate Slab 2	178	7.00
6	Substrate Slab 3		
7	Substrate Slab 3		
Overlay Placement 1 (May 7, 2016)			
1	Overlay Slab 1A	76	3.00
2	Overlay Slab 1B		
3	Overlay Slab 2A	25	1.00
4	Overlay Slab 3A		
Overlay Placement 2 (May 12, 2016)			
1	Overlay Slab 2B	44	1.75
2	Overlay Slab 3B		

4.2 Sack Concrete Sieve Analysis

A particle size distribution analysis was performed to determine the gradation of the aggregates within the proprietary sack concrete mix used in the research program. A representative sample was taken and tested on a laboratory sieve shaker. The analysis indicates that the proprietary concrete mix uses a coarse aggregate with a maximum particle size (D_{100}) of 12.7 mm (3/8 in).

4.3 Compression Testing Results

102 x 203 mm (4 x 8 in) sample cylinders were taken and tested for 12 of the 13 concrete batches used in the test program. Table 4.3-1 lists the maximum compression force recorded by the

Admet data logger for each cylinder. Table 4.3-2 lists the corresponding uniaxial compression stress in the cylinder at failure. A blank entry indicates no compression testing was performed for that batch. The two tests taken for each substrate slab were averaged to produce the substrate compressive strength, as shown in Table 4.3-3.

Table 4.3-1 – Compression force at failure

Batch No.	*Slab ID*	*3-Day*		*7-Day*		*28-Day*	
		kN	*kips*	*kN*	*kips*	*kN*	*kips*
Substrate Placement (April 7, 2016)							
1	Substrate Slab 1	125	28.1	243	54.6	333	74.8
2	Substrate Slab 1	187	42.1	262	58.9	348	78.3
3	Substrate Slab 2	187	42.0	272	61.2	324	72.8
4	Substrate Slab 2						
5	Substrate Slab 2	187	42.0	272	61.2	311	70.0
6	Substrate Slab 3	207	46.5	304	68.4	346	77.9
7	Substrate Slab 3	212	47.8	303	68.1	354	79.6
Overlay Placement 1 (May 7, 2016)							
1	Overlay Slab 1A	171	38.4	220	49.5	333	74.8
2	Overlay Slab 1B	212	47.6	203	45.7	385	86.4
3	Overlay Slab 2A	209	47.0	281	63.1	349	78.5
4	Overlay Slab 3A	227	51.0	237	53.3	368	82.7
Overlay Placement 2 (May 12, 2016)							
1	Overlay Slab 2B	107	24.2	139	31.3	259	58.1
2	Overlay Slab 3B	168	37.8	172	38.7	172	38.6

Table 4.3-2 –Compression stress at failure

Batch No.	*Slab ID*	*3-Day*		*7-Day*		*28-Day*	
		kPa	*psi*	*kPa*	*psi*	*kPa*	*psi*
Substrate Placement (April 7, 2016)							
1	Substrate Slab 1	15,396	2,233	29,941	4,343	41,046	5,953
2	Substrate Slab 1	23,099	3,350	32,295	4,684	42,961	6,231
3	Substrate Slab 2	23,028	3,340	33,600	4,873	39,959	5,796
4	Substrate Slab 2						
5	Substrate Slab 2	23,028	3,340	33,589	4,872	38,396	5,569
6	Substrate Slab 3	25,524	3,702	37,545	5,445	42,725	6,197
7	Substrate Slab 3	26,204	3,801	37,348	5,417	43,679	6,335
Overlay Placement 1 (May 7, 2016)							
1	Overlay Slab 1A	21,047	3,053	27,137	3,936	41,031	5,951
2	Overlay Slab 1B	26,106	3,786	25,052	3,634	47,429	6,879
3	Overlay Slab 2A	25,771	3,738	34,643	5,025	43,051	6,244
4	Overlay Slab 3A	27,982	4,058	29,222	4,238	45,388	6,583
Overlay Placement 2 (May 12, 2016)							
1	Overlay Slab 2B	13,256	1,923	17,146	2,487	31,888	4,625
2	Overlay Slab 3B	20,712	3,004	21,228	3,079	21,160	3,069

The results show that all substrate slabs, as well as the overlay slabs placed on May 7, achieved the design compressive strength of 34.5 MPa (5,000 psi). The compressive strengths of the overlay slabs placed on May 12 were lower than the design strength.

Table 4.3-3 – Average substrate compressive strength

Slab ID	*Substrate (kPa)*			*Substrate (psi)*		
	Test 1	*Test 2*	*Average*	*Test 1*	*Test 2*	*Average*
1	41,046	42,961	**42,003**	5,953	6,231	**6,092**
2	39,959	38,396	**39,178**	5,796	5,569	**5,683**
3	42,725	43,679	**43,203**	6,197	6,335	**6,266**

4.4 Specimen Identifiers

Each specimen tested as part of the pull-off, direct shear, slant shear, and jacking tests was assigned a sample I.D. The first two digits indicate the overlay slab where the specimen originated. The next number indicates the order in which the specimen was obtained, and the last letter indicates the type of test performed.

4.5 Pull-off Test Results

Three pull-off tests were performed on each of the six overlay slabs, for a total of 18 performed as part of the testing program. Table 4.5-1 lists the sample I.D. for each pull-off test; the letter 'T' indicates a Tension test. Images of each sample have been included in the Appendix. All specimens were observed to fail on or near the bond surface. Thirteen of the specimens failed at the bond surface; the remaining five specimens failed on the surface of the substrate.

Table 4.5-1 – Pull-off test samples

Slab ID	Pretreatments	Pull-off Test Sample I.D.		
		Test 1	Test 2	Test 3
1A	Dry / No Agent	1A1T	1A3T	1A5T
1B	Dry / Wet Agent	1B5T	1B7T	1B11T
2A	SSD / Wet Agent	2A3T	2A5T	2A7T
2B	SSD / Dried Agent	2B1T	2B3T	2B5T
3A	Wet / Wet Agent	3A1T	3A3T	3A5T
3B	SSD / No Agent	3B1T	3B3T	3B5T

The tensile strength at failure is listed on Table 4.5-2 (SI units) and Table 4.5-3 (U.S. customary units). A statistical analysis was performed on the dataset to compute the mean bond strength, standard deviation, and coefficient of variation.

Table 4.5-2 – Pull-off test results (SI units)

Slab ID	Pretreatments	Tensile Strength (kPa)			Statistical Analysis		
		Test 1	Test 2	Test 3	Average (kPa)	Std. Dev. (kPa)	COV
1A	Dry / No Agent	800	317	1,213	777	366	47.2%
1B	Dry / Wet Agent	1,069	1,296	1,048	1,138	112	9.9%
2A	SSD / Wet Agent	1,262	1,096	1,055	1,138	89	7.9%
2B	SSD / Dried Agent	379	372	124	292	119	40.7%
3A	Wet / Wet Agent	1,007	1,296	1,531	1,278	214	16.8%
3B	SSD / No Agent	814	1,096	1,758	1,223	396	32.4%

Table 4.5-3 – Pull-off test results (U.S. customary units)

Slab ID	*Pretreatments*	*Tensile Strength (psi)*			*Statistical Analysis*		
		Test 1	*Test 2*	*Test 3*	*Average (psi)*	*Std. Dev. (psi)*	*COV*
1A	Dry / No Agent	116	46	176	113	53.1	47.2%
1B	Dry / Wet Agent	155	188	152	165	16.3	9.9%
2A	SSD / Wet Agent	183	159	153	165	13.0	7.9%
2B	SSD / Dried Agent	55	54	18	42.3	17.2	40.7%
3A	Wet / Wet Agent	146	188	222	185	31.1	16.8%
3B	SSD / No Agent	118	159	255	177	57.4	32.4%

Past studies (Vaysburd & McDonald, 1999) indicate that the compressive strength of the concrete has a significant effect on the strength of the interfacial bond. Djazmati, et al. (2004) and Rosen (2016) compensate for unavoidable differences in compressive strength by dividing bond strength results by the square root of the compressive strength of the concrete (f'_c). Because the observed compressive strengths of the substrate and overlay differ in this study, the minimum compressive strength, $f'_{c(min)}$, was used for the adjustment. Table 4.5-4 (SI units) and Table 4.5-5 (U.S. customary units) list the factored bond strength results for the pull-off tests.

Table 4.5-4 – Pull-off test bond strength adjustment (SI units)

Slab ID	*Pretreatments*	*28 Day Compressive Strength (kPa)*		*Avg. Bond Strength in Tension (σ) (kPa)*	*Factored Bond Strength in Tension $\sigma / \sqrt{f'c_{(min)}}$*
		Substrate	*Overlay*		
1A	Dry / No Agent	42,003	41,031	777	3.83
1B	Dry / Wet Agent	42,003	47,429	1,138	5.55
2A	SSD / Wet Agent	39,179	43,051	1,138	5.75
2B	SSD / Dried Agent	39,179	31,888	292	1.63
3A	Wet / Wet Agent	43,203	45,388	1,278	6.15
3B	SSD / No Agent	43,203	21,160	1,223	8.41

Table 4.5-5 – Pull-off test bond strength adjustment (U.S. customary units)

Slab ID	*Pretreatments*	*28 Day Compressive Strength (psi)*		*Avg. Bond Strength in Tension (σ) (psi)*	*Factored Bond Strength in Tension*
		Substrate	*Overlay*		$\sigma / \sqrt{f'c}_{(min)}$
1A	Dry / No Agent	6092	5951	113	1.46
1B	Dry / Wet Agent	6092	6879	165	2.11
2A	SSD / Wet Agent	5683	6244	165	2.19
2B	SSD / Dried Agent	5683	4625	42.3	0.62
3A	Wet / Wet Agent	6266	6583	185	2.34
3B	SSD / No Agent	6266	3069	177	3.20

4.6 Direct Shear Test Results

Three direct shear tests were performed on each of the six overlay slabs, for a total of 18 performed as part of the testing program. All specimens were observed to fail on or near the bond surface. Sixteen of the specimens failed at the substrate surface; the remaining specimens (both on Slab 2B) failed on the surface of the overlay. Table 4.6-1 lists the sample I.D. for each direct shear test; the letter 'G' indicates a Guillotine test. Images of each sample have been included in the Appendix.

Table 4.6-1 – Direct shear test samples

Slab ID	*Pretreatments*	*Direct Shear Test Sample I.D.*		
		Test 1	*Test 2*	*Test 3*
1A	Dry / No Agent	1A2G	1A4G	1A7G
1B	Dry / Wet Agent	1B2G	1B8G	1B10G
2A	SSD / Wet Agent	2A2G	2A4G	2A6G
2B	SSD / Dried Agent	2B2G	2B4G	2B6G
3A	Wet / Wet Agent	3A2G	3A4G	3A6G
3B	SSD / No Agent	3B2G	3B4G	3B6G

The shear strength at failure is listed on Table 4.6-2 (SI units) and Table 4.6-3 (U.S. customary units). As with the pull-off results, a statistical analysis was performed on the dataset to compute the average shear strength, standard deviation, and coefficient of variation.

Table 4.6-2 – Direct shear test results (SI units)

Slab ID	*Pretreatments*	*Shear Strength at Interface (kPa)*			*Statistical Analysis*		
		Test 1	*Test 2*	*Test 3*	*Average (kPa)*	*Std. Dev. (kPa)*	*COV*
1A	Dry / No Agent	2,296	2,544	2,062	2,301	197	8.6%
1B	Dry / Wet Agent	3,316	3,027	2,916	3,087	169	5.5%
2A	SSD / Wet Agent	3,309	3,075	2,365	2,916	402	13.8%
2B	SSD / Dried Agent	655	1,496	1,420	1,191	380	31.9%
3A	Wet / Wet Agent	3,027	2,330	2,606	2,654	286	10.8%
3B	SSD / No Agent	2,675	2,730	3,192	2,866	232	8.1%

Table 4.6-3 – Direct shear test results (U.S. customary units)

Slab ID	*Pretreatments*	*Shear Strength at Interface (psi)*			*Statistical Analysis*		
		Test 1	*Test 2*	*Test 3*	*Average (psi)*	*Std. Dev. (psi)*	*COV*
1A	Dry / No Agent	333	369	299	334	28.6	8.6%
1B	Dry / Wet Agent	481	439	423	448	24.5	5.5%
2A	SSD / Wet Agent	480	446	343	423	58.2	13.8%
2B	SSD / Dried Agent	95	217	206	173	55.1	31.9%
3A	Wet / Wet Agent	439	338	378	385	41.5	10.8%
3B	SSD / No Agent	388	396	463	416	33.6	8.1%

Table 4.6-4 (SI units) and Table 4.6-5 (U.S. customary units) list the factored shear strength results for the direct shear tests. Reference the pull-off test results in Chapter 4.5 for further explanation of the adjustment factor.

Table 4.6-4 – Direct shear test strength adjustment (SI units)

Slab ID	*Pretreatments*	*28 Day Compressive Strength (kPa)*		*Avg. Interfacial Shear Strength (τ) (kPa)*	*Factored Interfacial Shear Strength $\tau / \sqrt{f'c}_{(min)}$*
		Substrate	*Overlay*		
1A	Dry / No Agent	42,003	41,031	2,301	11.36
1B	Dry / Wet Agent	42,003	47,429	3,087	15.06
2A	SSD / Wet Agent	39,179	43,051	2,916	14.73
2B	SSD / Dried Agent	39,179	31,888	1,191	6.67
3A	Wet / Wet Agent	43,203	45,388	2,654	12.77
3B	SSD / No Agent	43,203	21,160	2,866	19.70

Table 4.6-5 – Direct shear test strength adjustment (U.S. customary units)

Slab ID	*Pretreatments*	*28 Day Compressive Strength (psi)*		*Avg. Interfacial Shear Strength (τ) (psi)*	*Factored Interfacial Shear Strength $\tau / \sqrt{f'c}_{(min)}$*
		Substrate	*Overlay*		
1A	Dry / No Agent	6,092	5,951	334	4.33
1B	Dry / Wet Agent	6,092	6,879	448	5.74
2A	SSD / Wet Agent	5,683	6,244	423	5.61
2B	SSD / Dried Agent	5,683	4,625	173	2.54
3A	Wet / Wet Agent	6,266	6,583	385	4.86
3B	SSD / No Agent	6,266	3,069	416	7.50

4.7 Slant Shear Test Results

Four slant shear samples were taken from each of the six overlay slabs, for a total of 24. During extraction, four of these slant cores failed: three on Slab 2B, two on Slab 1B, and one on Slab 3A. The remaining eighteen specimens were tested in compression. As described in Chapter 3.2.5, all specimens were observed to fail in splitting tension, with none failing in shear on the bond surface. Table 4.7-1 lists the sample I.D. for each direct shear test; the letter 'S' indicates a Slant shear test. Images of each sample have been included in the Appendix.

Table 4.7-1 – Slant shear test samples

Slab ID	Pretreatments	Slant Shear Test Sample I.D.			
		Test 1	Test 2	Test 3	Test 4
1A	Dry / No Agent	1A1S	1A2S	1A3S	1A4S
1B	Dry / Wet Agent	1B1S		1B3S	
2A	SSD / Wet Agent	2A1S	2A2S	2A3S	2A4S
2B	SSD / Dried Agent	2B1S			
3A	Wet / Wet Agent		3A2S	3A3S	3A4S
3B	SSD / No Agent	3B1S	3B2S	3B3S	3B4S

The measured compression stress on the slant shear samples at failure is listed on Table 4.7-2 (SI units) and Table 4.7-3 (U.S. customary units).

Table 4.7-2 – Slant shear test results (SI units)

Slab ID	Pretreatments	Compression Stress at Failure (kPa)			
		Test 1	Test 2	Test 3	Test 4
1A	Dry / No Agent	37,411	25,662	33,219	36,860
1B	Dry / Wet Agent	41,341		40,569	
2A	SSD / Wet Agent	44,747	37,687	38,501	38,763
2B	SSD / Dried Agent	35,012			
3A	Wet / Wet Agent		29,979	27,593	36,391
3B	SSD / No Agent	39,066	30,916	36,446	26,641

Table 4.7-3 – Slant shear test results (U.S. customary units)

Slab ID	Pretreatments	Compression Stress at Failure (psi)			
		Test 1	Test 2	Test 3	Test 4
1A	Dry / No Agent	5,426	3,722	4,818	5,346
1B	Dry / Wet Agent	5,996		5,884	
2A	SSD / Wet Agent	6,490	5,466	5,584	5,622
2B	SSD / Dried Agent	5,078			
3A	Wet / Wet Agent		4,348	4,002	5,278
3B	SSD / No Agent	5,666	4,484	5,286	3,864

Based on the observed failure mode, it is apparent that the strength results were affected primarily by the compressive strength of the concrete, and not by the properties of the bond. Therefore, the slant shear test results have not been included in the results discussion or the conclusions of this study. Refer to Appendix E for additional information regarding the slant shear test results.

4.8 Jacking Test Results

Four jacking tests were performed on each of the six overlay slabs, for a total of 24 performed as part of the testing program. All specimens were observed to fail on the bond surface. Table 4.8-1 lists the sample I.D. for each jacking test; the letter 'J' indicates a Jacking test. Images of each sample have been included in the Appendix.

Table 4.8-1 – Jacking test samples

Slab ID	Pretreatments	Jacking Test Sample I.D.			
		Test 1	Test 2	Test 3	Test 4
1A	Dry / No Agent	1A1J	1A2J	1A3J	1A4J
1B	Dry / Wet Agent	1B1J	1B2J	1B3J	1B4J
2A	SSD / Wet Agent	2A1J	2A2J	2A3J	2A4J
2B	SSD / Dried Agent	2B1J	2B2J	2B3J	2B4J
3A	Wet / Wet Agent	3A1J	3A2J	3A3J	3A4J
3B	SSD / No Agent	3B1J	3B2J	3B3J	3B4J

The shear strength at failure is listed on Table 4.8-2 (SI units) and Table 4.8-3 (U.S. customary units). As with the pull-off results, a statistical analysis was performed on the dataset to compute the average shear strength, standard deviation, and coefficient of variation.

Table 4.8-2 – Jacking test results (SI units)

Slab ID	Pretreatments	Shear Strength at Interface (kPa)				Statistical Analysis		
		Test 1	Test 2	Test 3	Test 4	Average (kPa)	Std. Dev. (kPa)	COV
1A	Dry / No Agent	1,032	1,156	1,320	962	1,117	136	12.2%
1B	Dry / Wet Agent	1,209	1,307	1,206	1,034	1,189	98	8.2%
2A	SSD / Wet Agent	1,734	1,390	1,541	1,714	1,595	140	8.8%
2B	SSD / Dried Agent	820	827	1,081	1,117	961	138	14.4%
3A	Wet / Wet Agent	1,496	1,705	1,509	1,330	1,510	133	8.8%
3B	SSD / No Agent	1,182	1,571	1,871	1,525	1,537	244	15.9%

Table 4.8-3 – Jacking test results (U.S. customary units)

Slab ID	Pretreatments	Shear Strength at Interface (psi)				Statistical Analysis		
		Test 1	Test 2	Test 3	Test 4	Average (psi)	Std. Dev. (psi)	COV
1A	Dry / No Agent	150	168	192	140	162	19.7	12.2%
1B	Dry / Wet Agent	175	190	175	150	173	14.2	8.2%
2A	SSD / Wet Agent	252	202	224	249	231	20.3	8.8%
2B	SSD / Dried Agent	119	120	157	162	139	20.1	14.4%
3A	Wet / Wet Agent	217	247	219	193	219	19.3	8.8%
3B	SSD / No Agent	172	228	271	221	223	35.4	15.9%

Table 4.8-4 (SI units) and Table 4.8-5 (U.S. customary units) list the factored shear strength results for the jacking tests. Reference the pull-off test results for further explanation of the adjustment factor.

Table 4.8-4 – Jacking test strength adjustment (SI units)

Slab ID	Pretreatments	28 Day Compressive Strength (kPa)		Avg. Interfacial Shear Strength (τ) (kPa)	Factored Interfacial Shear Strength $\tau / \sqrt{f'c_{(min)}}$
		Substrate	Overlay		
1A	Dry / No Agent	42,003	41,031	1,117	5.52
1B	Dry / Wet Agent	42,003	47,429	1,189	5.80
2A	SSD / Wet Agent	39,179	43,051	1,595	8.06
2B	SSD / Dried Agent	39,179	31,888	961	5.38
3A	Wet / Wet Agent	43,203	45,388	1,510	7.26
3B	SSD / No Agent	43,203	21,160	1,537	10.6

Table 4.8-5 – Jacking test strength adjustment (U.S. customary units)

Slab ID	Pretreatments	28 Day Compressive Strength (psi)		Avg. Interfacial Shear Strength (τ) (psi)	Factored Interfacial Shear Strength $\tau / \sqrt{f'c_{(min)}}$
		Substrate	Overlay		
1A	Dry / No Agent	6,092	5,951	162	2.10
1B	Dry / Wet Agent	6,092	6,879	172	2.21
2A	SSD / Wet Agent	5,683	6,244	231	3.07
2B	SSD / Dried Agent	5,683	4,625	139	2.05
3A	Wet / Wet Agent	6,266	6,583	219	2.77
3B	SSD / No Agent	6,266	3,069	223	4.02

CHAPTER V

DISCUSSION

5.1 Variation of Compressive Strength

In general, the sack concrete used in this study produced relatively consistent 28-day strengths, despite some variability in the measured slump prior to placement. The average 28-day strength for the substrate and first overlay placements was 6,174 psi (42,566 kPa) with a coefficient of variation of just 6.2%. In contrast, the average 28-day strength for the second overlay placement was just 3,847 psi (26,525 kPa) with a coefficient of variation of 28.6%. The reason for this significant difference is not entirely certain. The concrete sacks used in both overlay placements were taken from the same shipment, and were kept covered between placements. One possible explanation is that the bags for the second overlay placement experienced increased humidity due to rainfall, which may have partially hydrated the cement.

Figure 5-1 shows the measured 28 day compressive strength for each substrate and overlay slab. Had the variation of compressive strengths not exceeded the observed differences in the substrate and first overlay placements, they may have been reasonably ignored in the comparison of bond strengths. However, the deviations were deemed significant enough to warrant adjustment to the bond strength results. The adjustment was made by dividing the recorded bond strength in tension or shear strength at the bonded interface by the square root of the concrete strength. The minimum of the substrate and overlay compressive strengths was used in the adjustment factor; it was assumed that the weaker slab would fail first and control the strength result. Equation (5-1) gives the solution for the factored bond strength in tension; Equation (5-2) gives the solution for the factored shear strength at the bonded interface.

$$Adjusted\ Bond\ Strength\ in\ Tension = \sigma \Big/ \sqrt{f'_{c,min}} \qquad (5\text{-}1)$$

Where: σ = measured bond strength in tension (kPa or psi)

$f'_{c,min}$ = minimum of overlay and substrate compressive strength (psi or kPa)

$$Adjusted\ Shear\ Strength\ at\ Interface = \tau \Big/ \sqrt{f'_{c,min}} \qquad (5\text{-}2)$$

Where: τ = measured shear strength at interface (kPa or psi)

$f'_{c,min}$ = minimum of overlay and substrate compressive strength (kPa or psi)

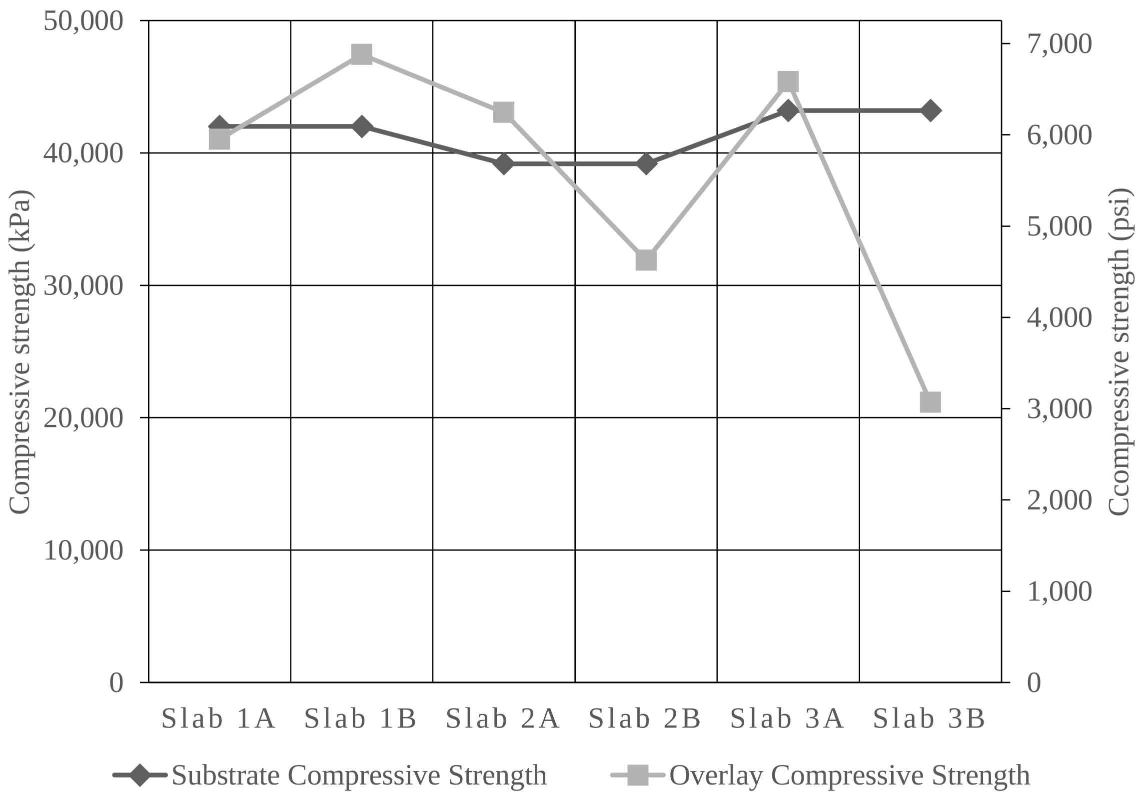


Figure 5-1 – 28-day compressive strength by slab location

5.2 Effects of Strength Gain on Test Results

Common engineering practice is to assume that the majority of strength gain in concrete is complete after 28 days of maturity. Accordingly, 28 day compressive strengths were used as adjustment factors to account for the difference in compressive strength between slabs, a process discussed previously in Chapter 5.1. The possible effects of strength gain after 28 days are discussed in the following paragraphs.

Using the strength gain data from the 3, 7, and 28 day tests, a maturity curve (Figure 5-2) was established based on a logarithmic function. Although no samples were tested after 28 days, the strength gain after 28 days may be estimated using the logarithmic function. The curve predicts a strength of 5813 psi (40,076 kPa) at 28 days. At 56 days, the concrete is expected to gain an additional 773 psi (5332 kPa) compressive strength, about 13.3% of the 28 day strength. However, between 56 and 72 days, the period in which the majority of the bond strength testing was conducted, the concrete is only expected to gain an additional 280 psi (1933 kPa), or about 4.3% of the 56 day strength.

With the exception of the pull-off tests, the results from each test were obtained in a single day. Clearly, the strength of concrete did not change appreciably during the day's testing; therefore, the results of any individual test type are unaffected by strength gain. It is only when the results of one type of test are compared with another that the effects of strength gain may be of concern. However, as was noted above, the estimated difference in compressive strength during the testing period is very minimal and may be reasonably ignored. Therefore, no adjustments were made to the bond strength results to compensate for the maturity of the concrete at the time of testing.

The logarithmic curve used to model strength gain was calculated using a least-squares best fit. This function is reproduced as Equation (5-3) in U.S. customary units.

$$f_c' = 1115.6 \ln(t) + 2095.1 \quad (5\text{-}3)$$

Where: f'_c = compressive strength of concrete (est.) (psi)

t = maturity, in days

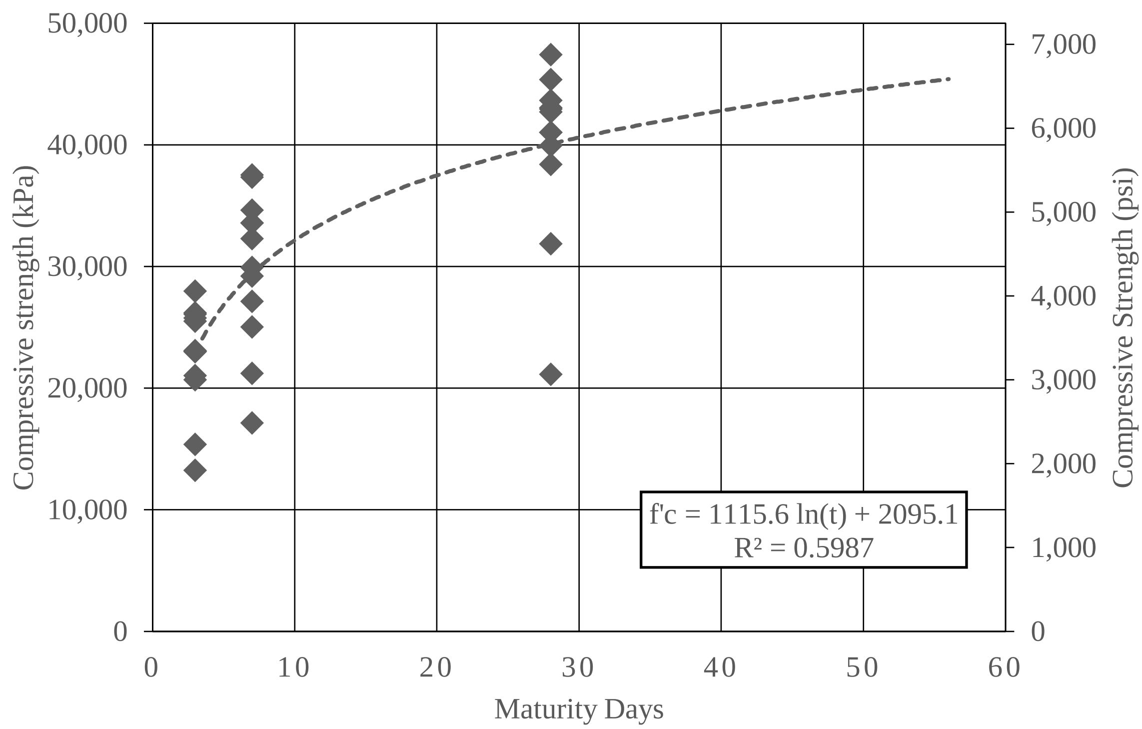


Figure 5-2 – Strength gain in concrete

5.3 Bond Strength in Tension

Figure 5-3 plots the average unadjusted bond strength in tension for each of the six pretreatment categories. Error is displayed as one standard deviation about the mean (±SD). The groupings shown on the horizontal axis represent the different types of pretreatments. The first term in the category title: “Dry”, “SSD”, or “Wet” represents the moisture condition of the substrate prior to overlay placement. The second term indicates whether a cement slurry bonding agent was used.

The results of the pull-off tests were adjusted for variations in the compressive strength of concrete and the average adjusted strength was plotted on Figure 5-4. With the exception of Slab 2B (discussed further below), the comparison shows that similar bond strengths were achieved in all samples prepared with an SSD substrate surface. The best performance was achieved in Slab 3B, which was prepared solely by prewetting the substrate. No detrimental impacts to strength were observed due to the overwet substrate surface treatment used in Slab 3A; these samples performed similarly to the SSD samples used in concert with a bonding agent.

The overlay on Slab 1A was applied directly to the profiled substrate with no prewetting and no bonding agent. This bond exhibited inferior performance relative to the other slabs. This is consistent with the conclusions of Bissonnette (2012) that a carefully controlled amount of moisture within the substrate can produce a better bond.

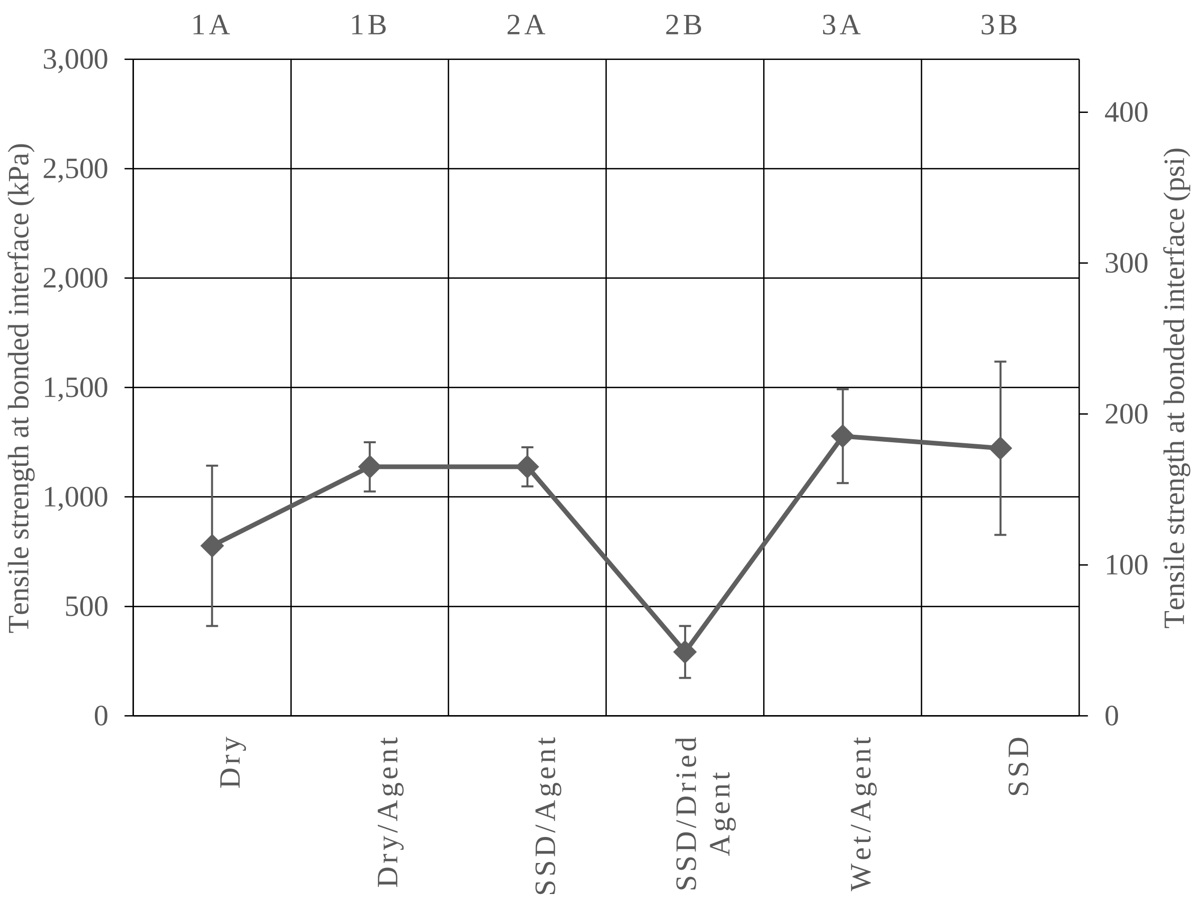


Figure 5-3 – Unadjusted average bond strengths in tension (±SD), grouped by pretreatment. N = 3 samples per pretreatment category.

The cement slurry on Slab 2B was allowed to dry for a period of several days prior to overlay placement. This bond was extremely poor relatively to the other samples tested. This substantiates a common concern with bonding agents, as expressed in ACI 325 and 345. The dried bonding agent, far from enhancing the bond strength, appears to act as a bond breaker. It is important that bonding agents remain wet until the moment the overlay concrete is placed.

The cement slurry bonding agent applied to a dry substrate (Slab 1B) performed similarly to the slabs prepared by prewetting. It appears that a properly applied bonding agent may benefit strength to a similar magnitude as prewetting, but the effect of both pretreatments in combination (Slab 2A) is not additive.

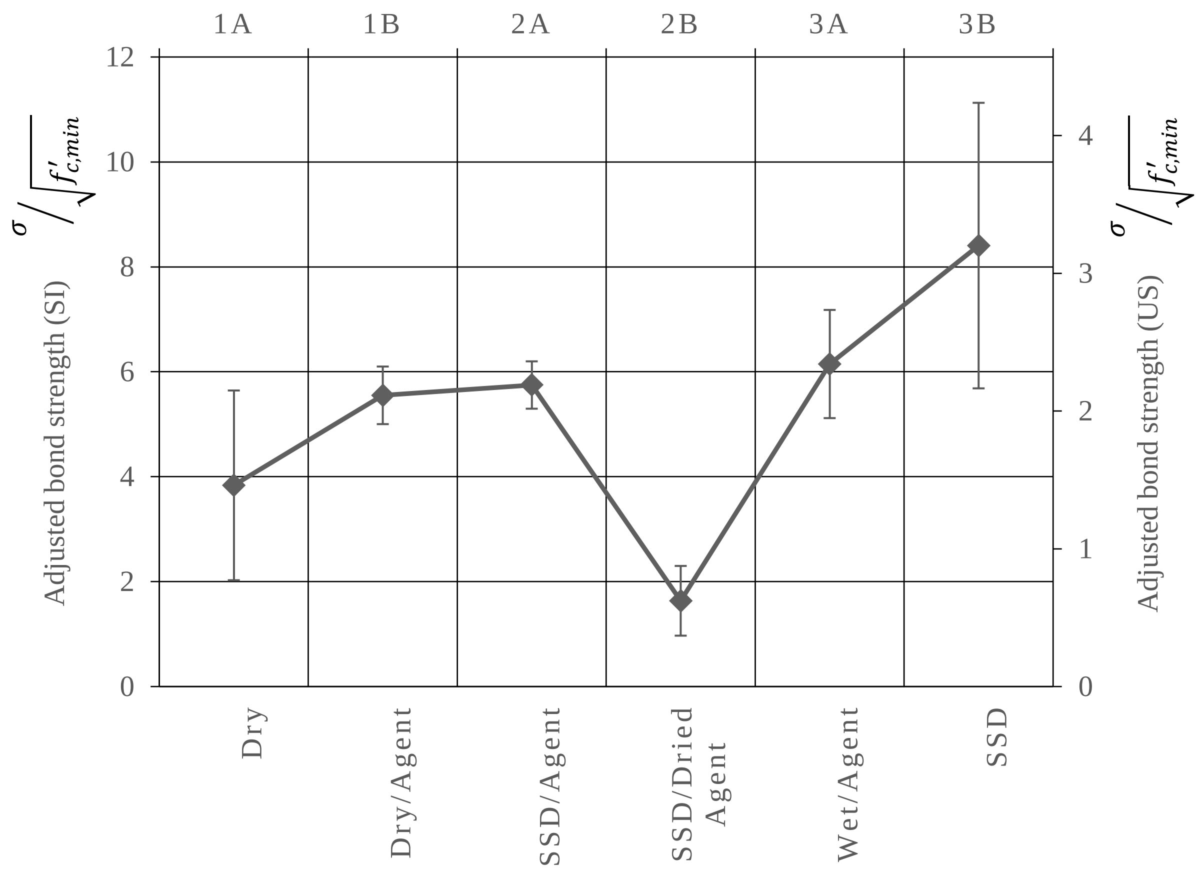


Figure 5-4 – Adjusted average bond strengths in tension (±SD), grouped by pretreatment. N=3 samples per pretreatment category.

5.4 Shear Strength at the Bonded Interface

5.4.1 Representative shear strengths from previous research

Published 'typical' values for shear strengths at bonded interfaces vary considerably by source. The AASHTO Bridge Design Specifications permit the designer to use a value of 1.93 MPa

(280 psi) for “clean concrete girder surfaces free of laitence with surface roughened to an amplitude of 0.25 in” (2014). Felt considered a shear strength of 2.24 MPa (325 psi) (measured in direct shear using a guillotine type jig) to be average; he classified samples that exceeded 2.76 MPa (400 psi) as “superior” (Felt, 1956). For adhesive bond strength, Silfwerbrand found an average value of about 1.0 MPa (145 psi) for surfaces prepared with a pnumatic hammer (Silfwerbrand, 1990). ACI 345 notes that 1.38 MPa (200 psi) is typically sufficent for durability (2006).

5.4.2 Direct shear test

Using typical shear strengths as a guide, Figure 5-5 indicates “superior” bond strengths were achieved in all slabs prepared with pretreatments (with the exception of Slab 2B, discussed below). The factored average shear strength measurements, adjusted for compressive strength of the concrete, are shown on Figure 5-6.

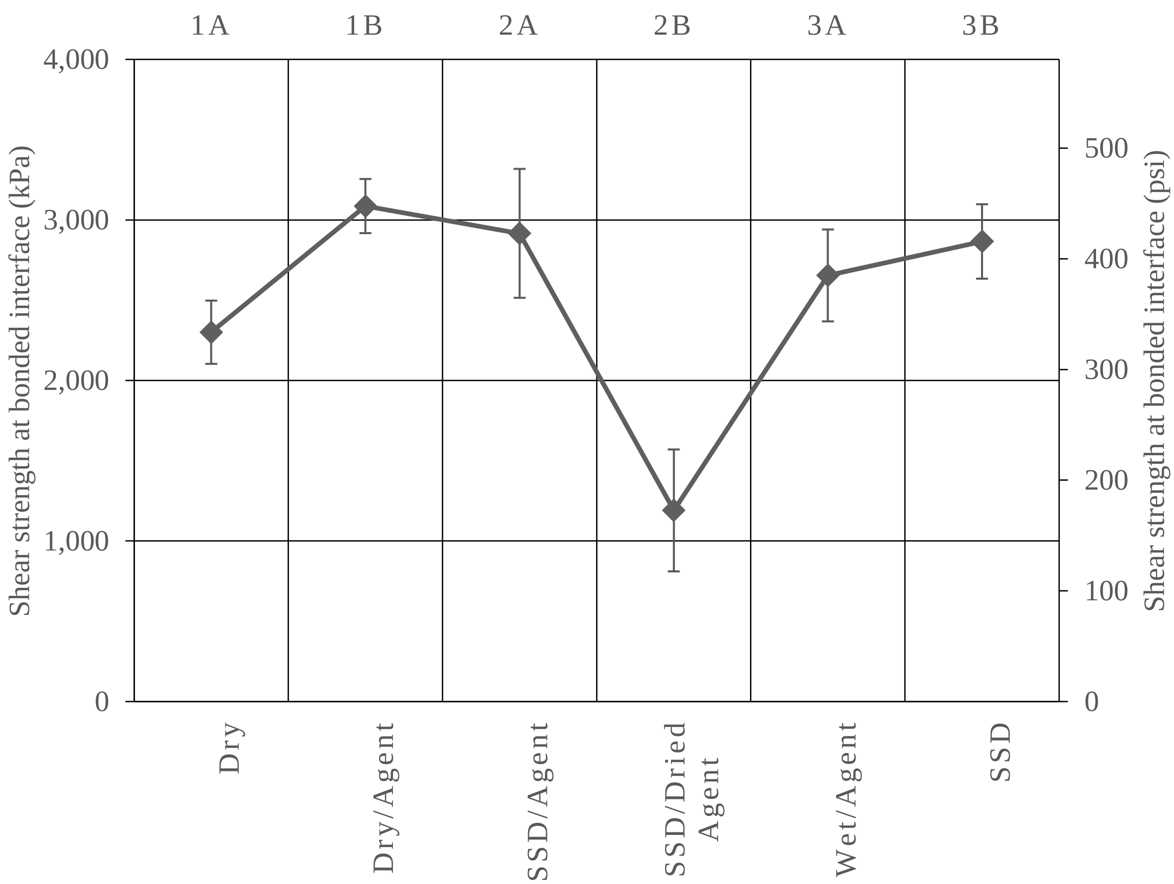


Figure 5-5 - Unadjusted average direct shear strengths (±SD) at the bonded interface, grouped by pretreatment. N=3 samples per pretreatment category.

The adjusted results show that the best performance was obtained from a substrate prepared solely by prewetting (Slab 3B). The overwet surface on Slab 3A appears to have had a detrimental effect on the measured strengths. The surface with no pretreatments (Slab 1A) performed poorly, as did the surface where the bonding agent was allowed to dry (Slab 2B).

The results indicate that a surface prepared solely with a bonding agent (Slab 1B) will perform similar to a surface prepared with a combination of prewetting and a bonding agent. The good performance of Slab 1B may be in part due to the wetting effect of the bonding agent. The bonding agent may form a barrier to prevent free water from the overlay concrete from being lost into the capillaries of the substrate. It may also encapsulate dust and other particles left behind after the cleaning that would otherwise prevent the overlay from bonding to the surface of the substrate (Silfwerbrand & Paulsson, 1998).

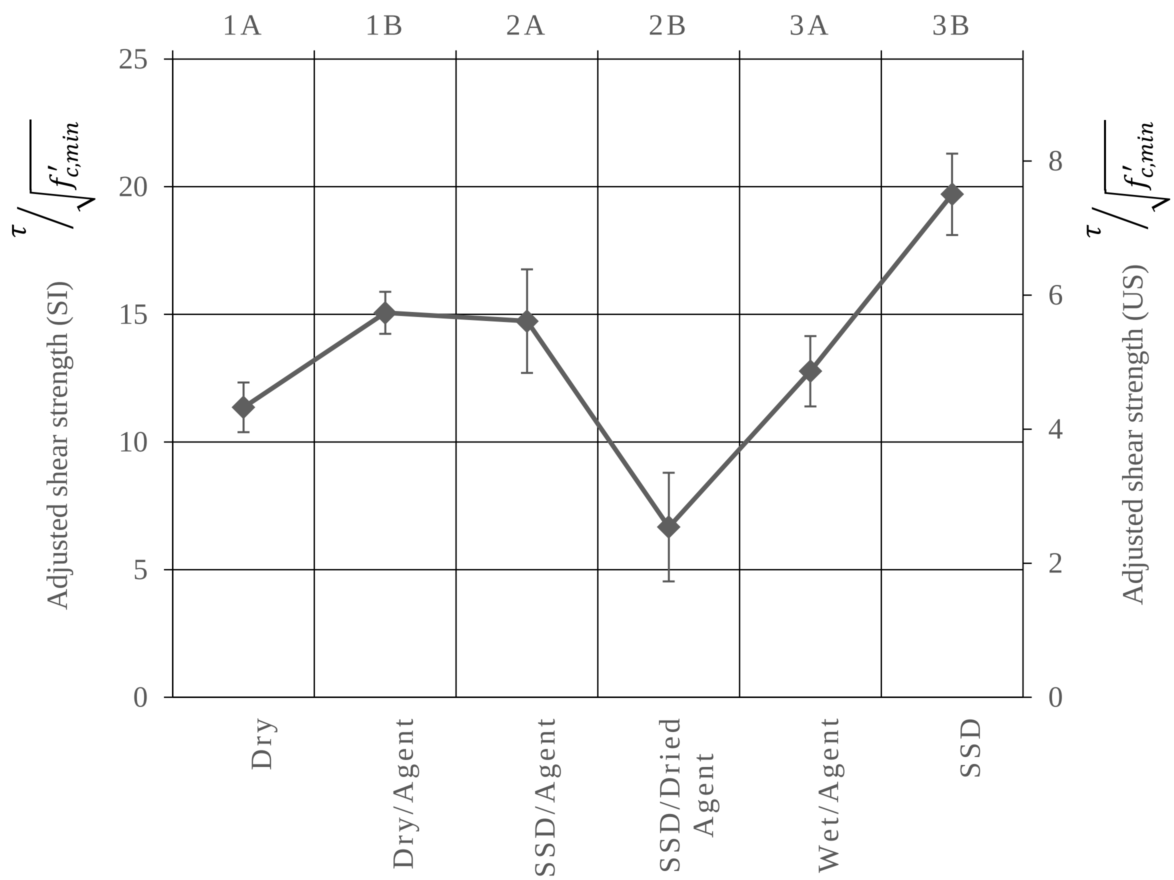


Figure 5-6 - Adjusted average direct shear strengths (±SD) at the bonded interface, grouped by pretreatment. N=3 samples per pretreatment category.

5.4.3 Slant shear tests

The observed failure mode of the slant shear specimens indicates that the results for the slant shear tests primarily reflect the average compressive strength of the overlay and substrate. These results do not appear to be influenced by the strength of the bond or by the pretreatments used.

5.4.4 Jacking test

Measured average jacking test results are shown on Figure 5-7, grouped by pretreatment type. The average results, adjusted for compressive strength of concrete, are shown on Figure 5-8. The highest adjusted strength results were obtained using an SSD slab with no bonding agent (Slab 3B). A SSD substrate surface used in conjuction with a bonding agent (Slab 2A) also performed well relative to the other surface preparations, as did the overwet substrate and bonding agent (Slab 3A), though neither performed as well as the prewet only substrate.

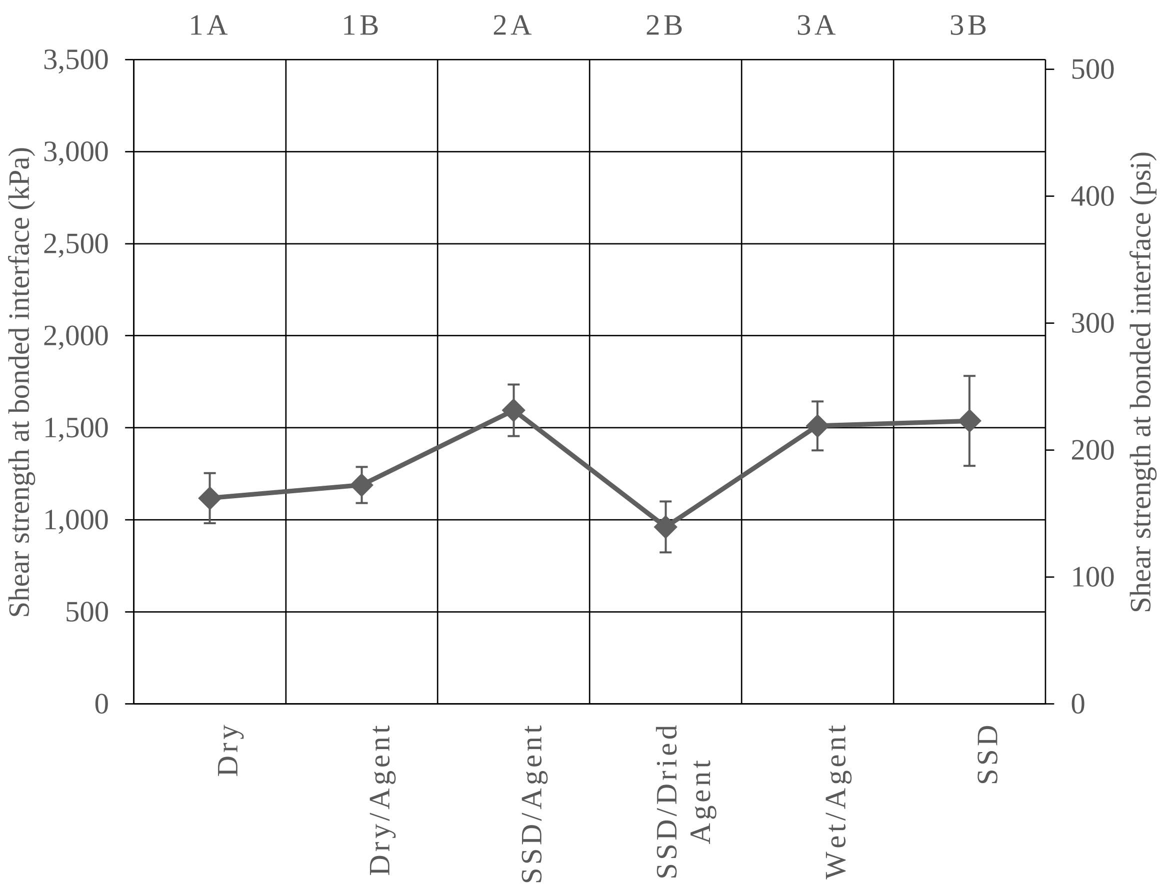


Figure 5-7 - Unadjusted average jacking test strengths (±SD) at the bonded interface, grouped by pretreatment. N=4 samples per pretreatment category.

The surface with no pretreatments (Slab 1A) obtained similar adjusted strengths as Slab 2B, where the bonding agent was allowed to dry. Other tests had obtained significantly lower strengths for the dried bonding agent relative to all other pretreatments. It is possible that the eccentricity caused by the location of the hydraulic piston during testing may be producing a clamping force at the opposite end of the block. This force may enhance the resistance to shearing due to mechanical interlock, such that even poorly pretreated surfaces exhibit shear resistance corresponding to their roughness.

Pretreating with a bonding agent alone (Slab 1B) did not produce superior shear strength relative to the other preparation methods. This is in contrast to the direct shear test, where the bonding agent alone produced strengths similar to those observed with prewetting.

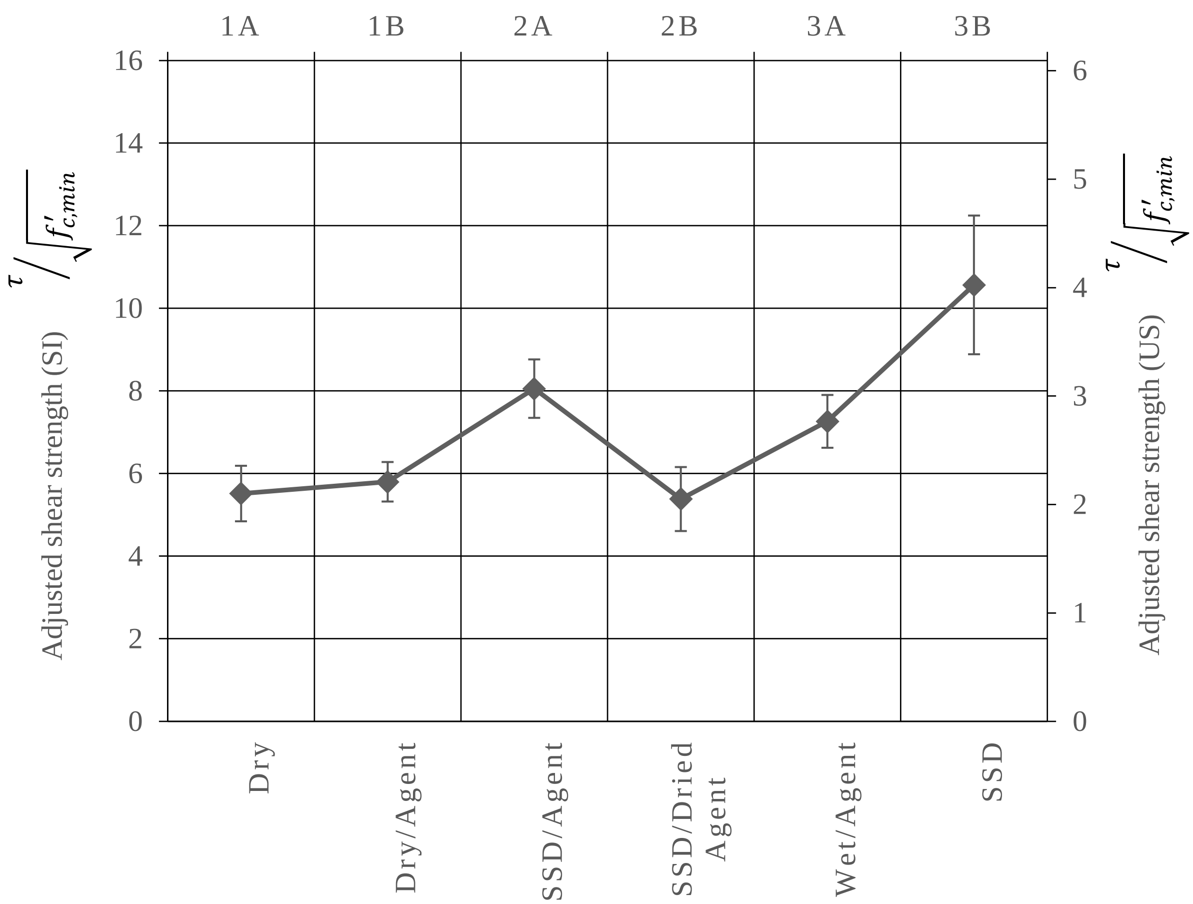


Figure 5-8 - Adjusted average jacking test strengths (±SD) at the bonded interface, grouped by pretreatment. N=4 samples per pretreatment category.

5.4.5 Comparison of shear test results

The direct shear and jacking tests both indicated that the best strength is achieved using prewetting only, with no bonding agent, and that the lowest strengths result from the improper application of a bonding agent (Slab 2B). Poor performance was also observed when no pretreatments were used (Slab 1A).

The shear tests produced conflicting results when comparing the effect of prewetting in conjunction with a bonding agent (Slabs 1B and 2A): the jacking test indicated that prewetting had an beneficial effect on bond strength, while the direct shear results indicated the opposite. The results are inconclusive; it appears that a properly applied bonding agent may benefit in strength to a similar magnitude as prewetting for some testing conditions. However, it can be ascertained that the effect of both pretreatments used in combination is not additive.

5.4.6 Comparison of tension and shear test results

All three tests agree that the best bond strength in tension and shear is obtained when the substrate surface is SSD and no bonding agent is used. When a bonding agent is used in combination with a SSD surface, all tests indicate some reduction in strength in comparison with the prewet-only surface. The surface prepared with a dried bonding agent performed poorly in all types of tests. Additionally, the surface prepared with no pretreatments performed poorly relatively to the pretreated slabs for both tension and shear tests.

The tension and shear tests responded differently to the overwet substrate surface on Slab 3A. The shear tests both indicated that the overwet surface had a slightly detrimental effect on shear strength, which the pull-off test showed no distinct difference in strength between the overwet surface of Slab 3A and the SSD surface of Slab 2A.

The unadjusted direct shear results and pull-off test results are plotted on Figure 5-9 (SI units) and Figure 5-10 (US customary units). Clearly, it is not possible to obtain the strength of a single sample using more than one test, so the x,y coordinates of the datapoints are taken from the same test number (Test 1-3) for each of the two tests (pull-off and direct shear). The pull-off and direct shear samples were cored on the same day in alternating order along the length of the test slab. Test sample one for the direct shear test was taken immediately adjacent to test sample 1 for the pull-off test, and so on for test samples two and three.

Figure 5-10 shows that, though there is considerable scatter in the data, there may be a linear relationship between shear strength at the bonded interface and bond strength in tension. If a best fit line is calculated using the least-squares method and this line is made to go through the origin, Equation (5-4) is obtained.

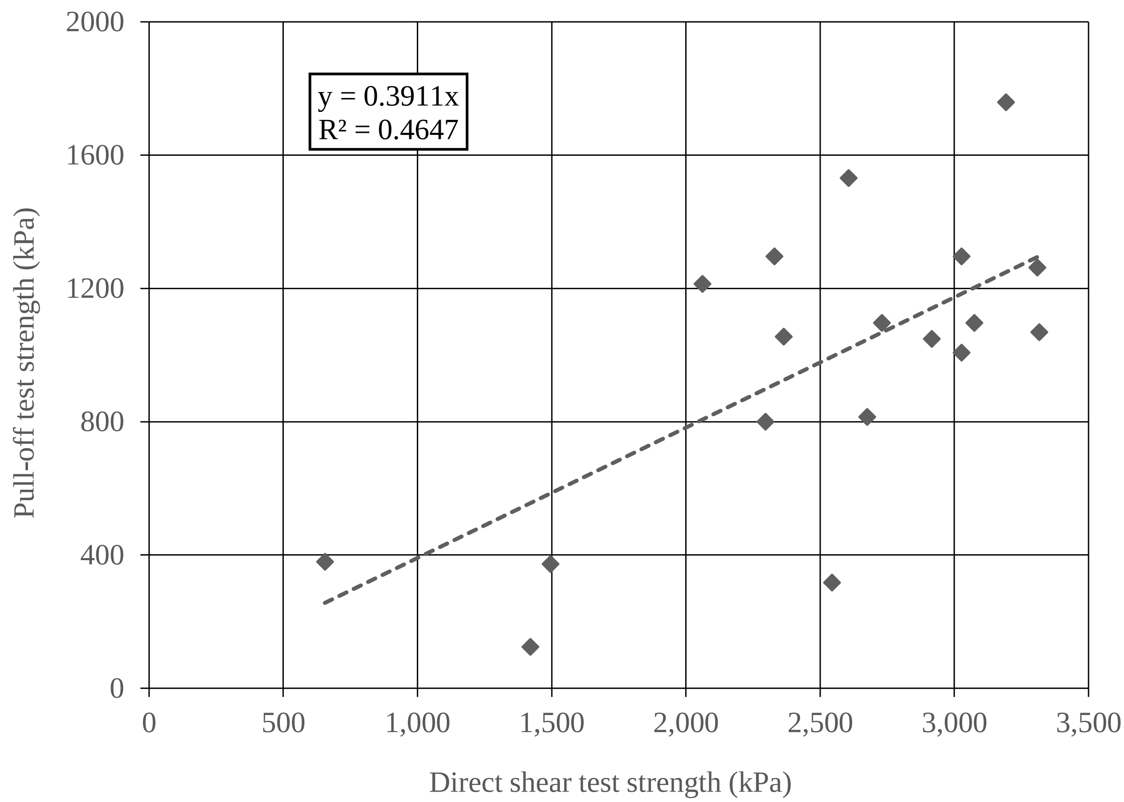


Figure 5-9 - Direct shear vs. pull-off test results (SI units)

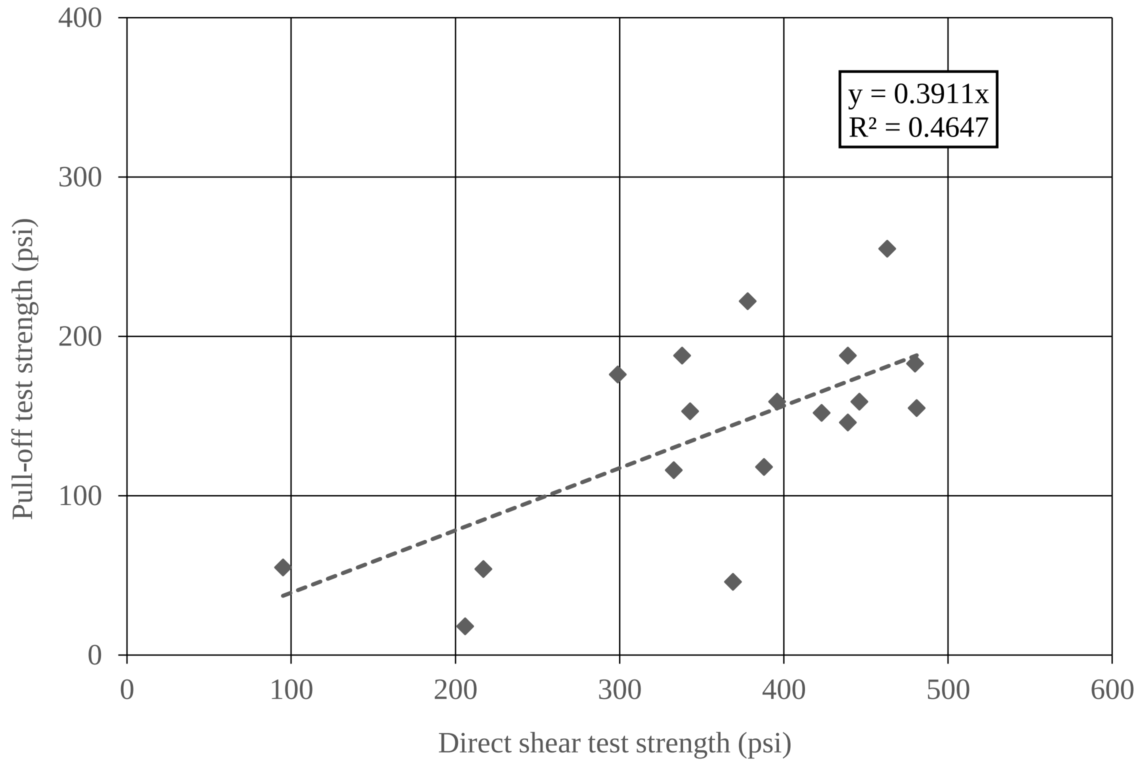


Figure 5-10 – Direct shear vs. pull-off test results (U.S. customary units)

$$\sigma = 0.3911\,\tau \tag{5-4}$$

Where: σ = Tensile strength of bond (est.) (kPa or psi)

τ = Shear strength at bonded interface (kPa or psi)

If the equation is inverted, the conversion factor from tensile strength to shear strength is calculated as 2.56. Considering the multitude of factors involved in this comparison, this correlates reasonably well with the 2.04 factor determined by Delatte, et al. (2000), and used by Rosen (2016).

5.4.7 Variations in data

Figure 5-11 plots the coefficient of variation for each pretreatment and test type. Relatively low variation was observed for most of the pretreatment/test combinations. Relatively high variation (CV > 30%) in the pull off test results was observed at Slabs 1A, 2B, and 3B. The variation at Slab 2B is easily explained: the adhesive strengths measured for this slab were so low that they were close to the lower limit of the measuring capacity of the device. At low levels of stress, small differences in measurement result in large coefficients of variation. The variation at Slabs 1A and 3B cannot be as easily explained, as their average shear strengths were comparable to the neighboring slabs. Instead, it appears that the high variation in pull-off test results may be attributed to the lack of bonding agent on these slabs. The bonding agent, while not significantly increasing bond strength, decreases the variability of the bond, an effect first noted by Felt (1956) and corroborated by Saucier and Pigeon (1991). The same effect appears to occur in the jacking test results, though it is not nearly as pronounced. A similar effect was not observed in the direct shear test results.

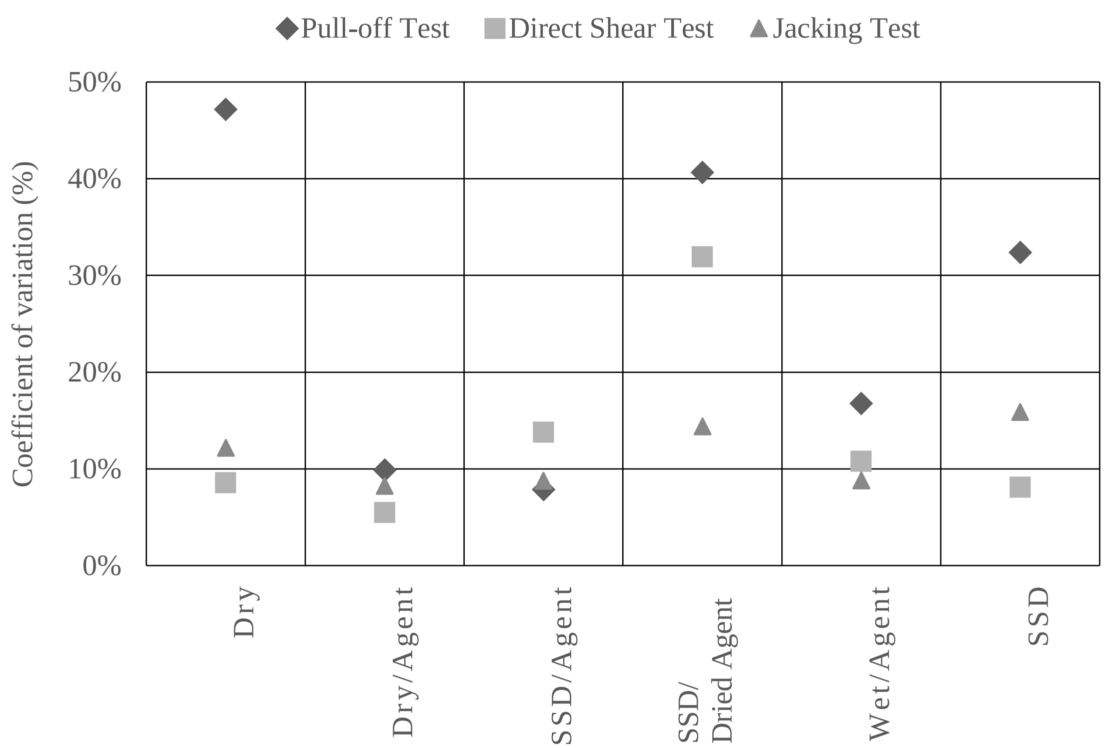


Figure 5-11 – Coefficients of variation for each test type, grouped by pretreatment

5.4.8 Statistical significance

A statistical analysis of the strength results was undertaken to further corroborate the observations regarding the effects of pretreatments. A similar analysis was performed by Wall and Shrive (1988). A Student's t-test was performed using datasets gathered from five combinations of pre-treatments to determine if the observed differences were statistically significant. A significant difference was deemed to occur at the 90 percent confidence interval. The results of the analysis are shown in Table 5.4-1.

Table 5.4-1 – Results of statistical analysis

Pre-treatment		Significant Difference (Y or N) (90% CI)		
Moisture	Bonding Agent	Pull-off	Direct Shear	Jacking
Dry Substrate	No Agent vs. Wet Agent	N	Y	N
SSD Substrate	Dry Agent vs. Wet Agent	Y	Y	Y
Dry vs. SSD Substrate	No Agent	N	Y	Y
Dry vs. SSD Substrate	Wet Agent	N	N	Y
SSD vs. Wet Substrate	Wet Agent	N	N	N

Not surprisingly, all three tests indicate a significant difference between the strength obtained with a wet bonding agent versus one that has been left to dry. The direct shear test indicated a significant difference in strength when bonding agent was applied on a dry substrate, although the jacking test did not substantiate this result. The direct shear and jacking tests both identified that a significant difference in strength was achieved using an SSD substrate versus a dry substrate in the absence of a bonding agent. The jacking test also identified this difference when a bonding agent was used. None of the tests identified a significant statistical difference between a SSD and wet substrate.

CHAPTER VI

SUMMARY AND CONCLUSIONS

6.1 Summary

Prewetting the substrate and the use of a bonding agent are both common practices in the construction of bonded concrete overlays and other types of repairs, yet the efficacy of these pretreatments is often debated. The program of research described herein was undertaken to identify best practices with regards to pretreatment. To that end, three substrate and six overlay slabs were constructed, and each substrate surface was prepared with a different combination of pretreatments. Samples from each slab were subjected to a number of tests to evaluate the impact on bond strength in tension and shear strength at the bonded interface. The conclusions, below, are derived from the experimental data:

6.2 Conclusions

The results indicate that pretreatments can substantially improve the strength of concrete-to-concrete bond. Compared with an overlay constructed with no pretreatments, the overlay placed on the saturated surface dry substrate, using a properly applied bonding agent, achieved 46 percent greater bond strength in tension and 35 percent greater strength in shear. However, the inappropriate use of pretreatments can hinder the development of bond between substrate and overlay. When the bonding agent was improperly applied, the bond strength in tension decreased by 62 percent and the shear strength decreased by 31 percent, as compared to the slab constructed with no pretreatments.

Prewetting of the substrate generally produced superior bond strengths, irrespective of the use of bonding agents. For some tests, overlays prepared with a combination of prewetting and a bonding agent performed somewhat better than overlays prepared solely by prewetting. Concern regarding overwetting the substrate surface appears to be largely unfounded; an overwet substrate surface (one containing small puddles of water) performed better in the tension test and slightly worse in the shear tests, but the overall effect was minor.

The effect on strength of the use of a bonding agent in the absence of prewetting was inconclusive. Two of the tests indicated superior bond strength, while the third saw no strength benefit. However, the application of a bonding agent did reduce the variability of the bond strength in the pull-off (tension) test. This effect was not observed in the shear tests. Allowing the bonding agent to dry on the substrate prior to overlay placement had an extreme negative effect on bond strength for all types of tests.

In general, reasonably good bond strengths were obtained using a saturated surface dry substrate alone. Prewetting the substrate substantially increased strength under both tensile and shear stresses, and the risk of overwetting the substrate appears to be minimal. The designer should consider specifying an SSD substrate whenever good concrete-to-concrete bond strength is desired.

The designer should weigh the increase to bond strength resulting from the application of a bonding agent with the potential drawbacks due to improper application. If the application is carefully controlled, the bonding agent may provide some benefit.

In some cases, the pull-off, direct shear, and jacking tests responded differently to combinations of pre-treatments. The designer should consider specifying the test which best mimics the loads to which the repair will be subjected.

6.3 Suggestions for Future Research

There are numerous ways in which this program of research may be extended. These can be generally grouped into two categories: 1) incorporating other methods of testing bond strength or 2) evaluating other methods of slab preparation and pretreatment.

In the first category, the literature teems with alternative methods of measuring bond strength in tension and shear strength at the bonded interface. Among these are a twist-off (torsion) type test described by Whitney, et al. (1992) and a tensile slant shear test described by Austin, et al. (1999). These and other tests could be incorporated into a new program of research to evaluate their sensitivities to the effects of pretreatments.

In the second category, the research discussed herein evaluated the effects of pretreatments on a single ICRI Concrete Surface Profile. It is reasonable to assume that the effects of bonding agents may become more pronounced as the amplitude of surface roughness decreases. A new program of research could be undertaken to determine the interaction between pretreatments and substrate surface roughness.

Silfwerbrand and Paulsson (1998) note that the scrubbing action during application of a bonding agent may assimilate dust particles that were not removed by cleaning, thereby improving the strength of the concrete-to-concrete bond. A program of research could be undertaken to determine if scrubbing water into the substrate surface would have a similar effect.

Certain authors, such as Whitney, et al. (1992) had previously observed that bonding agents can be very effective in hot weather when the temperature of the substrate is elevated. A program of research could be undertaken to assess the impact of ambient temperature on the effectiveness of pretreatments.

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APPENDIX A

PULL OFF TEST DATA

Appendix A contains recorded data from the ASTM C1583 tensile strength (pull-off) tests. Specimens are grouped by slab number. The tensile force at failure, measured using the pull-off apparatus, is given for each specimen. The tensile stress at failure is calculated based on the tensile force and gross bonded area.

ASTM C1583 PULL-OFF TEST DATA

Test:	ASTM C1583 (Pull-off test)	Test Date:	As Noted
Slab I.D.:	Slab 1A		
Moisture:	Dry	Tested by:	ASP
Bonding Agent:	None		
Core Diameter:	66.7 mm (2 5/8 in)		

SPECIMEN 1A1T (6/22/2016)					
		SI Units		Imperial Units	
	Tensile Force at Failure	2.80	kN	630	lbs
	Tensile Stress at Failure	800	kPa	116	psi
SPECIMEN 1A3T (6/21/2016)					
		SI Units		Imperial Units	
	Tensile Force at Failure	1.11	kN	250	lbs
	Tensile Stress at Failure	317	kPa	46	psi
SPECIMEN 1A5T (6/26/2016)					
		SI Units		Imperial Units	
	Tensile Force at Failure	4.23	kN	950	lbs
	Tensile Stress at Failure	1213	kPa	176	psi

ASTM C1583 PULL-OFF TEST DATA

Test:	ASTM C1583 (Pull-off test)	Test Date:	As Noted
Slab I.D.:	Slab 1B		
Moisture:	Dry	Tested by:	ASP
Bonding Agent:	Cement Slurry (Wet)		
Core Diameter:	66.7 mm (2 5/8 in)		

SPECIMEN 1B5T (6/26/1016)

	SI Units		Imperial Units	
Tensile Force at Failure	3.74	kN	840	lbs
Tensile Stress at Failure	1069	kPa	155	psi

SPECIMEN 1B7T (6/26/2016)

	SI Units		Imperial Units	
Tensile Force at Failure	4.54	kN	1020	lbs
Tensile Stress at Failure	1296	kPa	188	psi

SPECIMEN 1B11T (8/4/2016)

	SI Units		Imperial Units	
Tensile Force at Failure	3.65	kN	820	lbs
Tensile Stress at Failure	1048	kPa	152	psi

ASTM C1583 PULL-OFF TEST DATA

Test:	ASTM C1583 (Pull-off test)	Test Date:	As Noted
Slab I.D.:	Slab 2A		
Moisture:	SSD	Tested by:	ASP
Bonding Agent:	Cement Slurry (Wet)		
Core Diameter:	66.7 mm (2 5/8 in)		

SPECIMEN 2A3T (6/26/1016)			
		SI Units	Imperial Units
	Tensile Force at Failure	4.41 kN	990 lbs
	Tensile Stress at Failure	1262 kPa	183 psi

SPECIMEN 2A5T (6/26/2016)			
		SI Units	Imperial Units
	Tensile Force at Failure	3.83 kN	860 lbs
	Tensile Stress at Failure	1096 kPa	159 psi

SPECIMEN 2A7T (8/4/2016)			
		SI Units	Imperial Units
	Tensile Force at Failure	3.69 kN	830 lbs
	Tensile Stress at Failure	1055 kPa	153 psi

ASTM C1583 PULL-OFF TEST DATA

Test:	ASTM C1583 (Pull-off test)	Test Date:	6/22/2016
Slab I.D.:	Slab 2B		
Moisture:	SSD	Tested by:	ASP
Bonding Agent:	Cement Slurry (Dried)		
Core Diameter:	66.7 mm (2 5/8 in)		

SPECIMEN 2B1T

	SI Units		Imperial Units	
Tensile Force at Failure	1.34	kN	300	lbs
Tensile Stress at Failure	379	kPa	55	psi

SPECIMEN 2B3T

	SI Units		Imperial Units	
Tensile Force at Failure	1.29	kN	290	lbs
Tensile Stress at Failure	372	kPa	54	psi

SPECIMEN 2B5T

No Photo Available

	SI Units		Imperial Units	
Tensile Force at Failure	0.45	kN	100	lbs
Tensile Stress at Failure	124	kPa	18	psi

ASTM C1583 PULL-OFF TEST DATA

Test:	ASTM C1583 (Pull-off test)	Test Date:	6/26/2016
Slab I.D.:	Slab 3A		
Moisture:	Overwet (small puddles)	Tested by:	ASP
Bonding Agent:	Cement Slurry (Wet)		
Core Diameter:	66.7 mm (2 5/8 in)		

SPECIMEN 3A1T

	SI Units		Imperial Units	
Tensile Force at Failure	3.52	kN	790	lbs
Tensile Stress at Failure	1007	kPa	146	psi

SPECIMEN 3A3T

	SI Units		Imperial Units	
Tensile Force at Failure	4.54	kN	1020	lbs
Tensile Stress at Failure	1296	kPa	188	psi

SPECIMEN 3A5T

	SI Units		Imperial Units	
Tensile Force at Failure	5.34	kN	1200	lbs
Tensile Stress at Failure	1531	kPa	222	psi

ASTM C1583 PULL-OFF TEST DATA

Test:	ASTM C1583 (Pull-off test)	Test Date:	6/26/2016
Slab I.D.:	Slab 3B		
Moisture:	SSD	Tested by:	ASP
Bonding Agent:	None		
Core Diameter:	66.7 mm (2 5/8 in)		

SPECIMEN 3B1T					
		SI Units		Imperial Units	
	Tensile Force at Failure	2.85	kN	640	lbs
	Tensile Stress at Failure	814	kPa	118	psi

SPECIMEN 3B3T					
		SI Units		Imperial Units	
	Tensile Force at Failure	3.83	kN	860	lbs
	Tensile Stress at Failure	1096	kPa	159	psi

SPECIMEN 3B5T					
		SI Units		Imperial Units	
	Tensile Force at Failure	6.14	kN	1380	lbs
	Tensile Stress at Failure	1758	kPa	255	psi

APPENDIX B

DIRECT SHEAR (GUILLOTINE) TEST DATA

Appendix B contains recorded data from the direct shear (guillotine) tests. Specimens are grouped by slab number. The maximum shearing force applied, measured using the MTS equipment, is given for each specimen. The shear stress at failure is calculated based on the recorded shearing force (divided by two) and gross bonded area. The stress-strain plot is based on the recorded load-displacement data, converted to stress and strain using the gross bonded area and diameter of specimen, respectively.

DIRECT SHEAR TEST DATA

Test:	Direct Shear (Guillotine) Test	Test Date:	7/11/2016
Slab I.D.:	Slab 1A		
Moisture:	Dry	Tested by:	ASP
Bonding Agent:	None		
Core Diameter:	66.7 mm (2 5/8 in)		

SPECIMEN 1A2G

	SI Units		Imperial Units	
Applied Load at Failure	16.0	kN	3604	lbs
Shear Stress at Failure	2296	kPa	333	psi

SPECIMEN 1A4G

	SI Units		Imperial Units	
Applied Load at Failure	17.8	kN	3995	lbs
Shear Stress at Failure	2544	kPa	369	psi

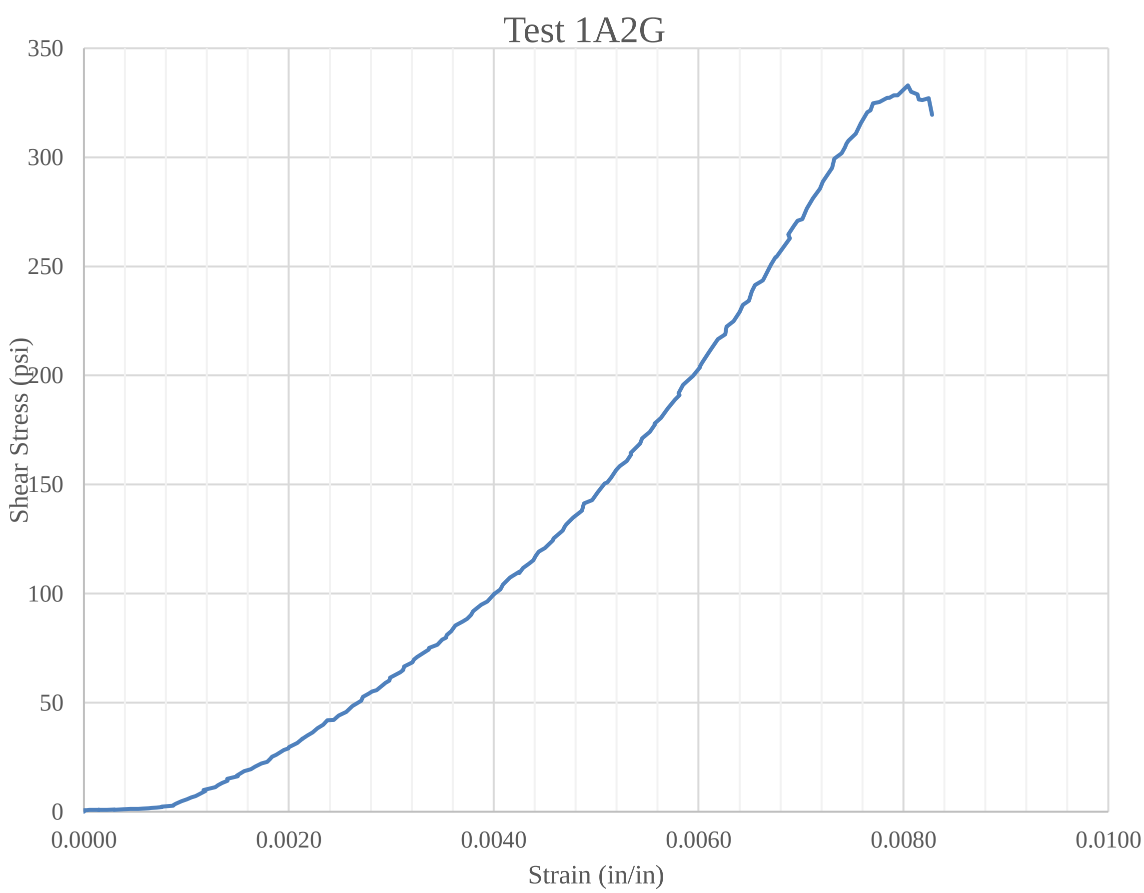
SPECIMEN 1A7G

	SI Units		Imperial Units	
Applied Load at Failure	14.4	kN	3233	lbs
Shear Stress at Failure	2062	kPa	299	psi

DIRECT SHEAR TEST DATA

Test:	Direct Shear (Guillotine) Test	Test Date:	7/11/2016
Slab I.D.:	Slab 1A		
Moisture:	Dry	Tested by:	ASP
Bonding Agent:	None		
Core Diameter:	66.7 mm (2 5/8 in)		

SPECIMEN 1A2G

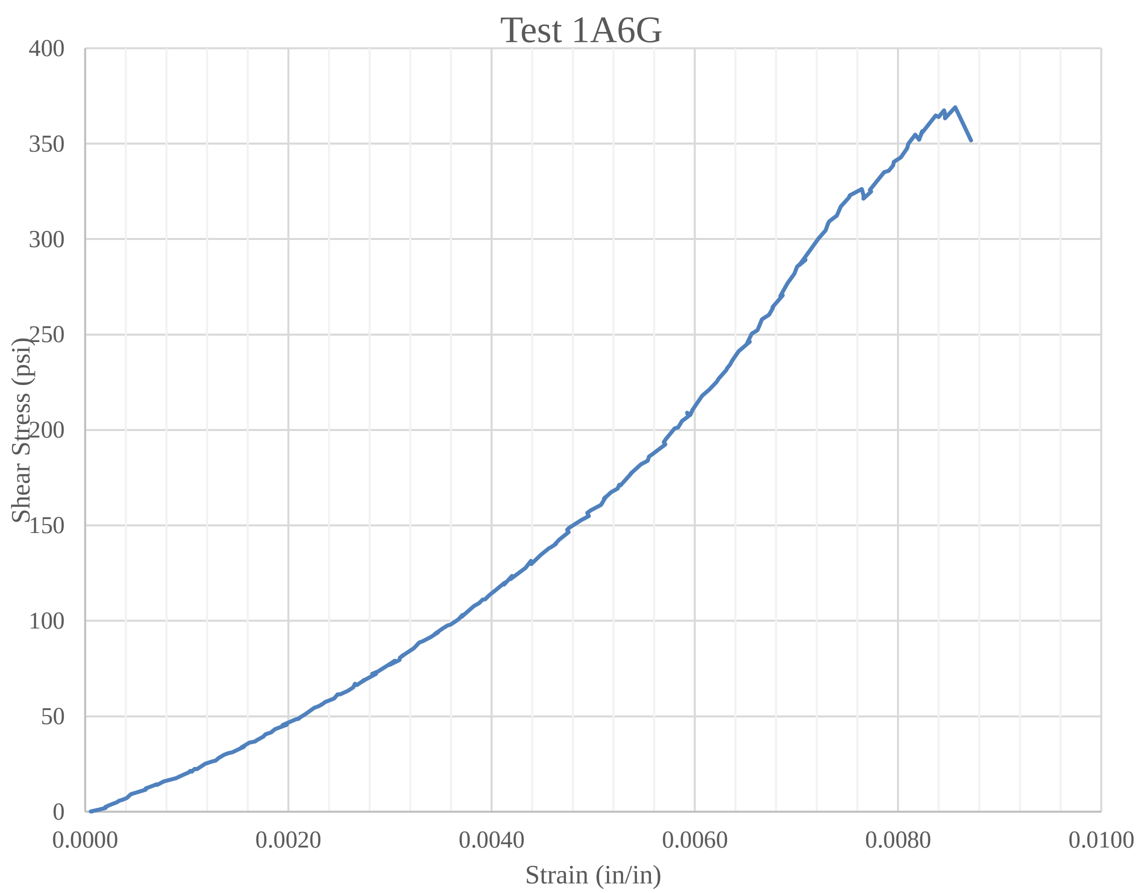


Maximum Load:	3604	lbs
Maximum Stress:	333	psi
Strain at Failure:	0.0080	in/in

DIRECT SHEAR TEST DATA

Test:	Direct Shear (Guillotine) Test	Test Date:	7/11/2016
Slab I.D.:	Slab 1A		
Moisture:	Dry	Tested by:	ASP
Bonding Agent:	None		
Core Diameter:	66.7 mm (2 5/8 in)		

SPECIMEN 1A6G



Maximum Load:	3995	lbs
Maximum Stress:	369	psi
Strain at Failure:	0.0086	in/in

DIRECT SHEAR TEST DATA

Test:	Direct Shear (Guillotine) Test	Test Date:	7/11/2016
Slab I.D.:	Slab 1B		
Moisture:	Dry	Tested by:	ASP
Bonding Agent:	Cement Slurry (Wet)		
Core Diameter:	66.7 mm (2 5/8 in)		

SPECIMEN 1B2G

	SI Units	Imperial Units
Applied Load at Failure	23.2 kN	5204 lbs
Shear Stress at Failure	3316 kPa	481 psi

SPECIMEN 1B8G

	SI Units	Imperial Units
Applied Load at Failure	21.2 kN	4757 lbs
Shear Stress at Failure	3027 kPa	439 psi

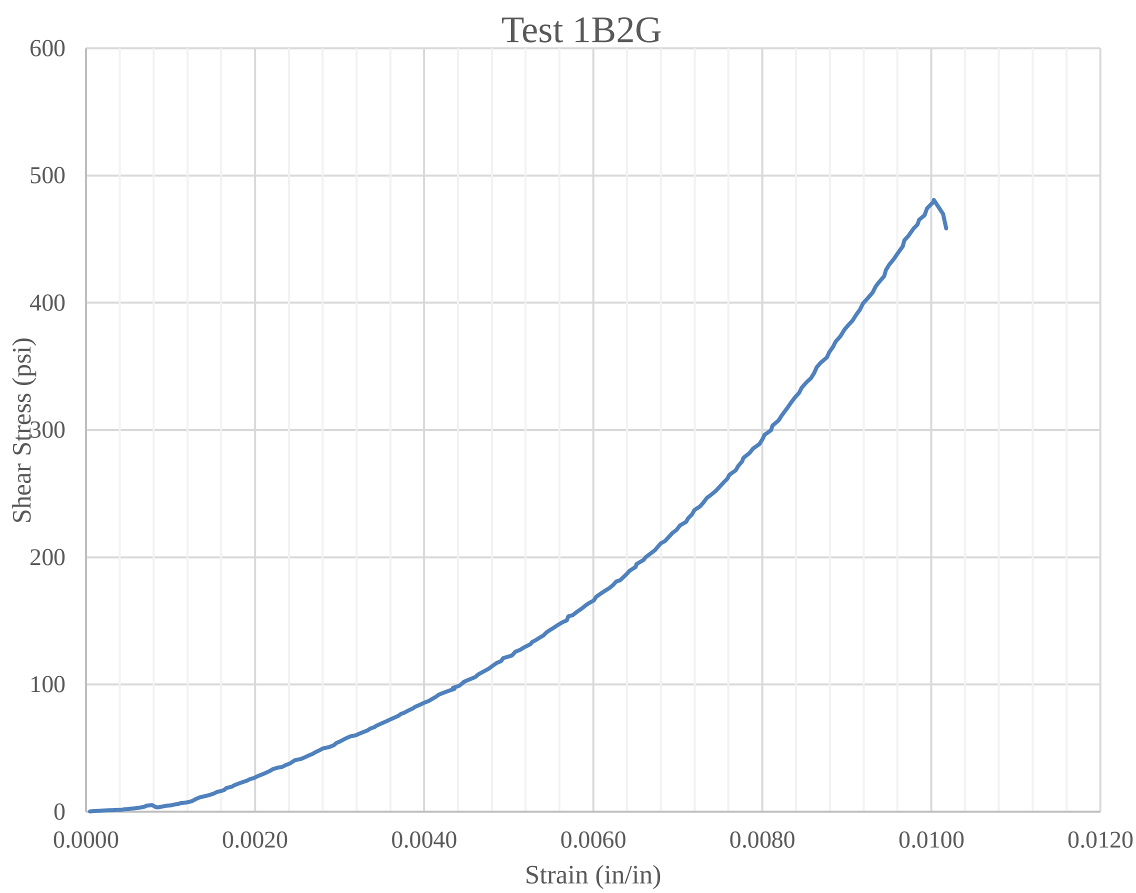
SPECIMEN 1B10G

	SI Units	Imperial Units
Applied Load at Failure	20.4 kN	4580 lbs
Shear Stress at Failure	2916 kPa	423 psi

DIRECT SHEAR TEST DATA

Test:	Direct Shear (Guillotine) Test	Test Date:	7/11/2016
Slab I.D.:	Slab 1B		
Moisture:	Dry	Tested by:	ASP
Bonding Agent:	Cement Slurry (Wet)		
Core Diameter:	66.7 mm (2 5/8 in)		

SPECIMEN 1B2G

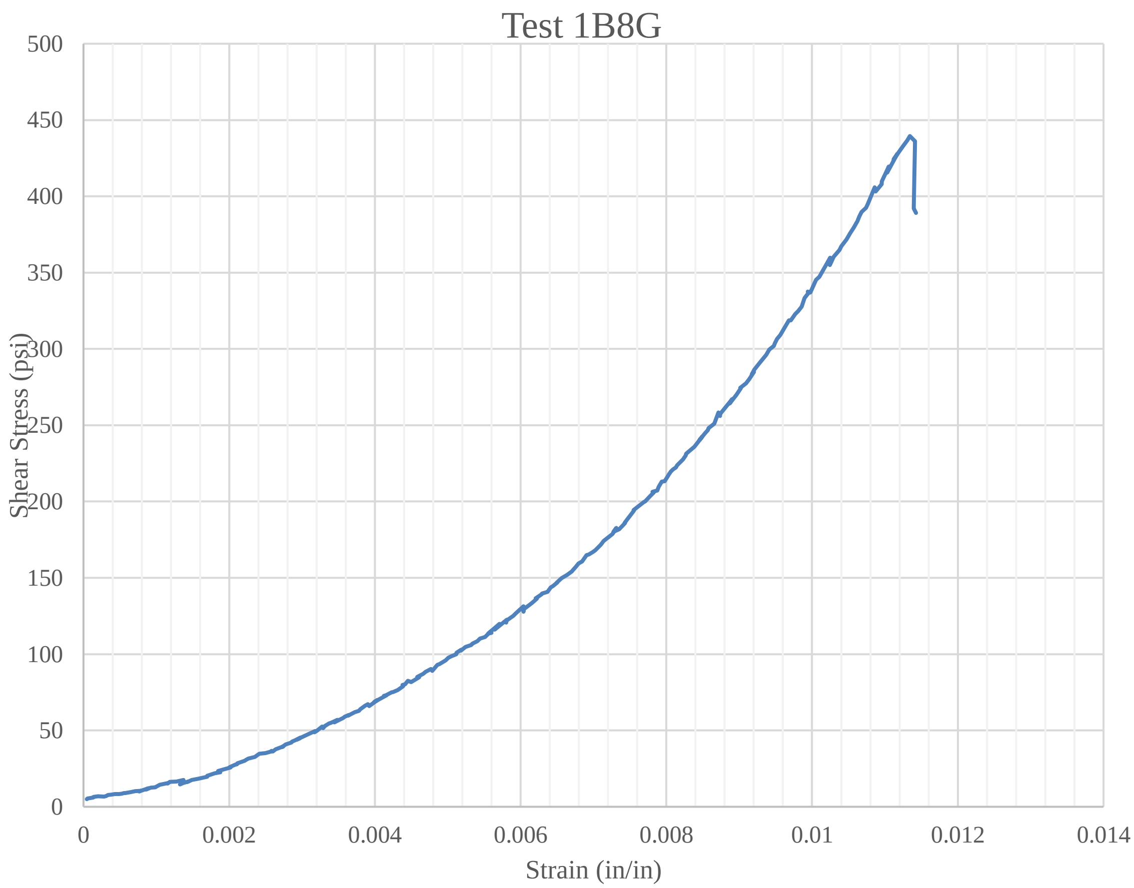


Maximum Load:	5204	lbs
Maximum Stress:	481	psi
Strain at Failure:	0.0100	in/in

DIRECT SHEAR TEST DATA

Test:	Direct Shear (Guillotine) Test	Test Date:	7/11/2016
Slab I.D.:	Slab 1B		
Moisture:	Dry	Tested by:	ASP
Bonding Agent:	Cement Slurry (Wet)		
Core Diameter:	66.7 mm (2 5/8 in)		

SPECIMEN 1B8G

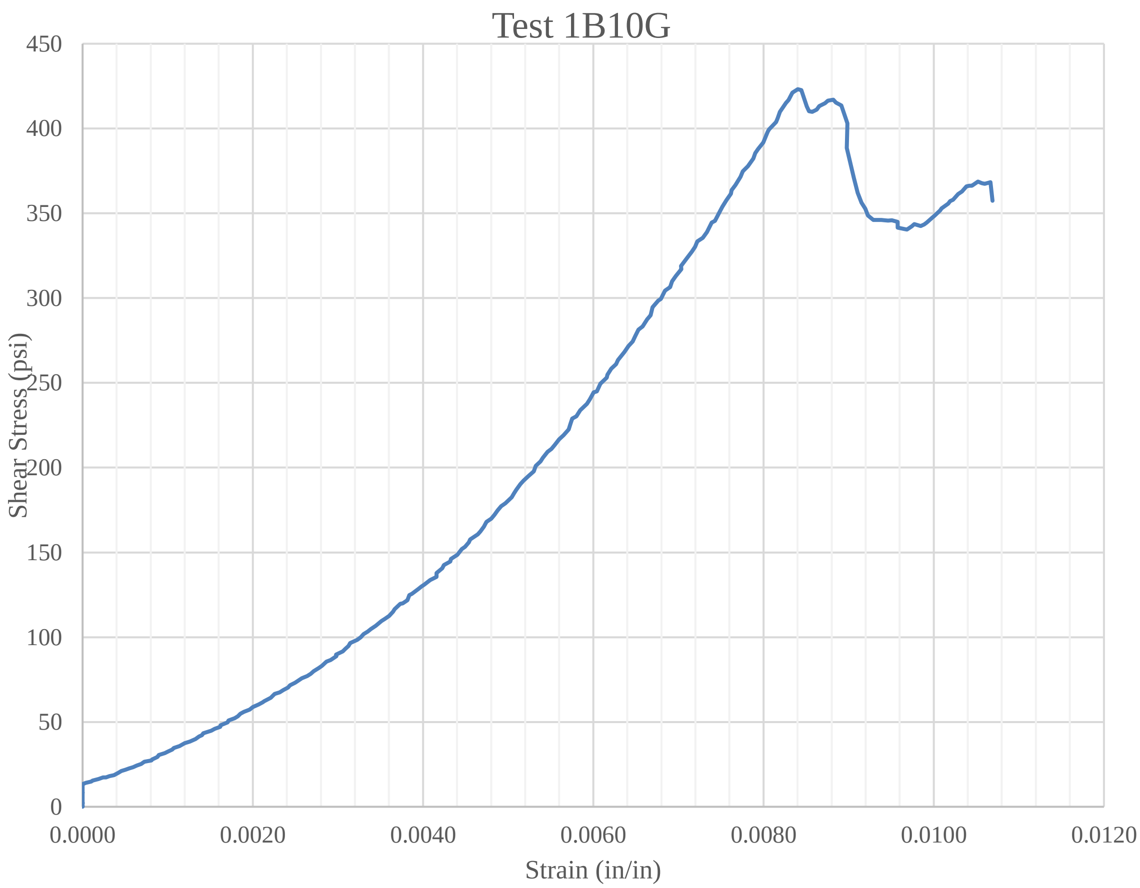


Maximum Load:	4757	lbs
Maximum Stress:	439	psi
Strain at Failure:	0.0113	in/in

DIRECT SHEAR TEST DATA

Test:	Direct Shear (Guillotine) Test	Test Date:	7/11/2016
Slab I.D.:	Slab 1B		
Moisture:	Dry	Tested by:	ASP
Bonding Agent:	Cement Slurry (Wet)		
Core Diameter:	66.7 mm (2 5/8 in)		

SPECIMEN 1B10G



Maximum Load:	4580	lbs
Maximum Stress:	423	psi
Strain at Failure:	0.0084	in/in

DIRECT SHEAR TEST DATA

Test:	Direct Shear (Guillotine) Test	Test Date:	7/11/2016
Slab I.D.:	Slab 2A		
Moisture:	SSD	Tested by:	ASP
Bonding Agent:	Cement Slurry (Wet)		
Core Diameter:	66.7 mm (2 5/8 in)		

SPECIMEN 2A2G

	SI Units		Imperial Units	
Applied Load at Failure	23.1	kN	5200	lbs
Shear Stress at Failure	3309	kPa	480	psi

SPECIMEN 2A4G

	SI Units		Imperial Units	
Applied Load at Failure	21.5	kN	4828	lbs
Shear Stress at Failure	3075	kPa	446	psi

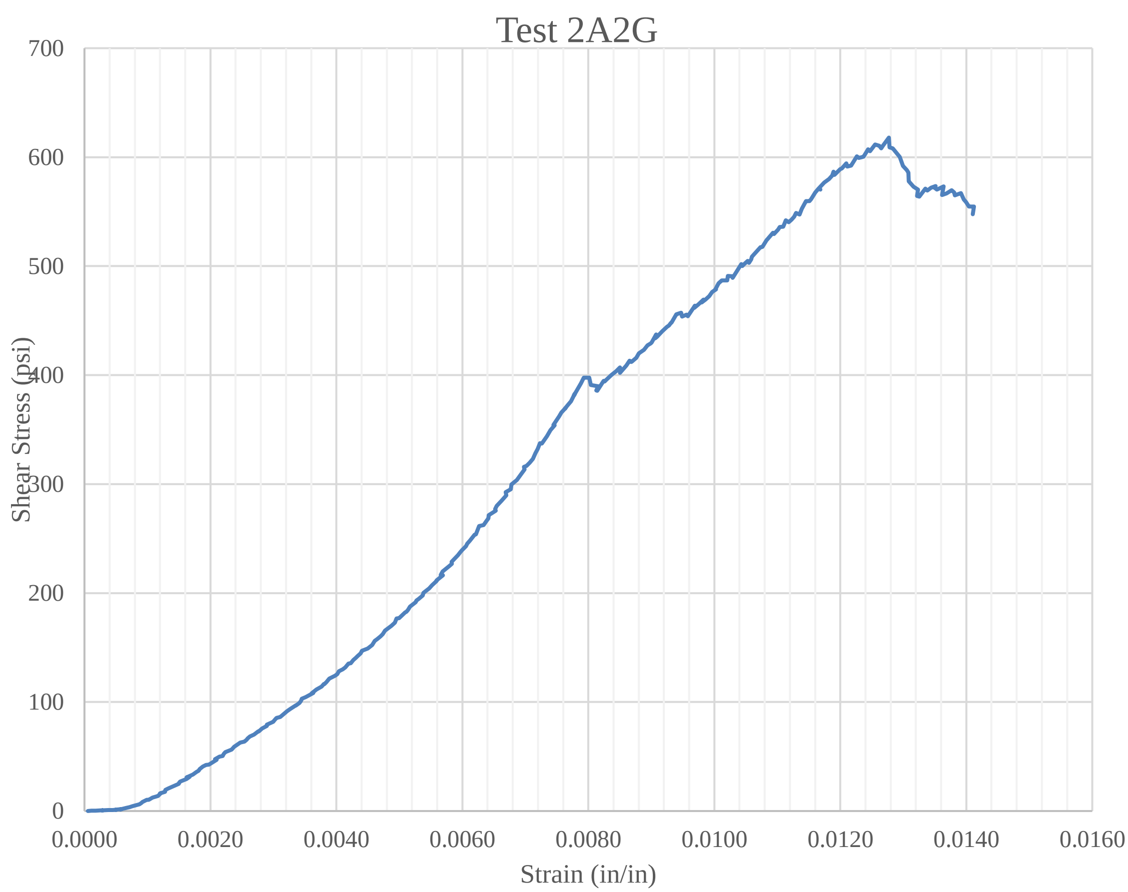
SPECIMEN 2A6G

	SI Units		Imperial Units	
Applied Load at Failure	16.5	kN	3711	lbs
Shear Stress at Failure	2365	kPa	343	psi

DIRECT SHEAR TEST DATA

Test:	Direct Shear (Guillotine) Test	Test Date:	7/11/2016
Slab I.D.:	Slab 2A		
Moisture:	SSD	Tested by:	ASP
Bonding Agent:	Cement Slurry (Wet)		
Core Diameter:	66.7 mm (2 5/8 in)		

SPECIMEN 2A2G

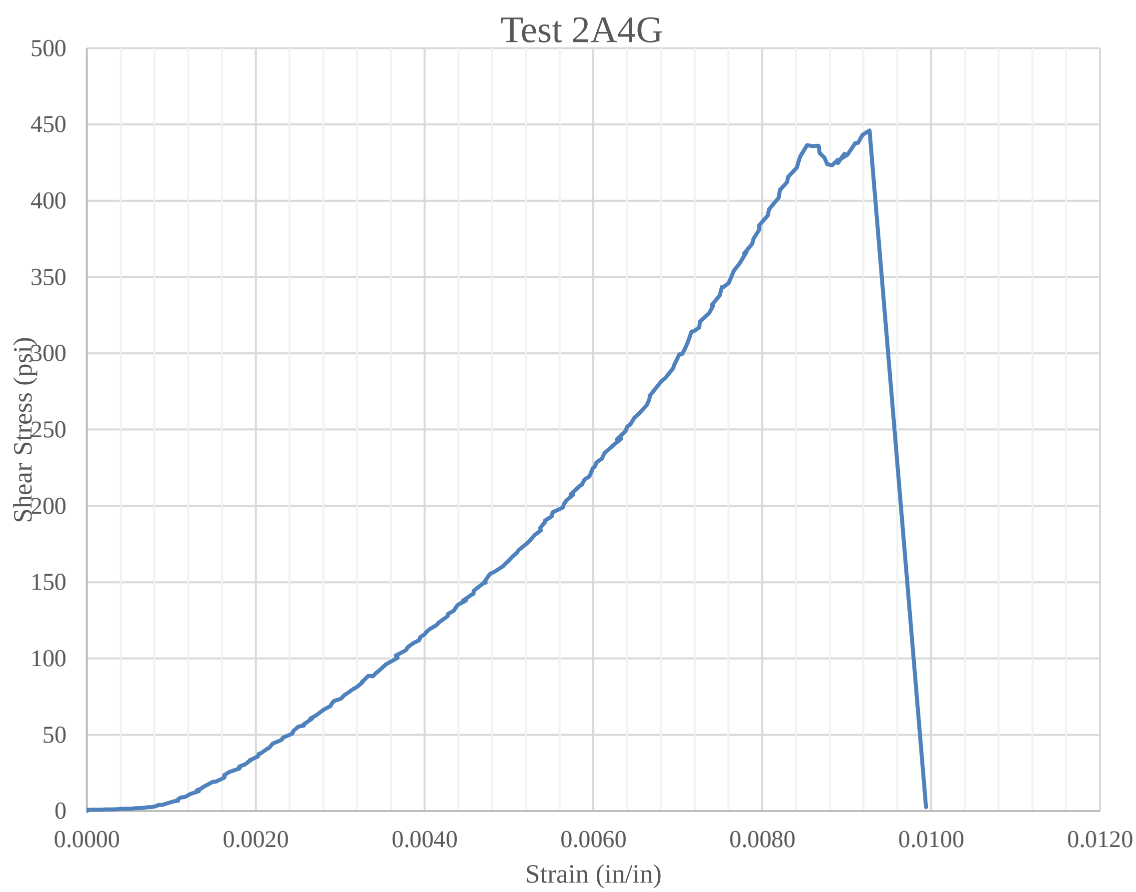


Maximum Load:	5200	lbs
Maximum Stress:	480	psi
Strain at Failure:	0.0128	in/in

DIRECT SHEAR TEST DATA

Test:	Direct Shear (Guillotine) Test	Test Date:	7/11/2016
Slab I.D.:	Slab 2A		
Moisture:	SSD	Tested by:	ASP
Bonding Agent:	Cement Slurry (Wet)		
Core Diameter:	66.7 mm (2 5/8 in)		

SPECIMEN 2A4G

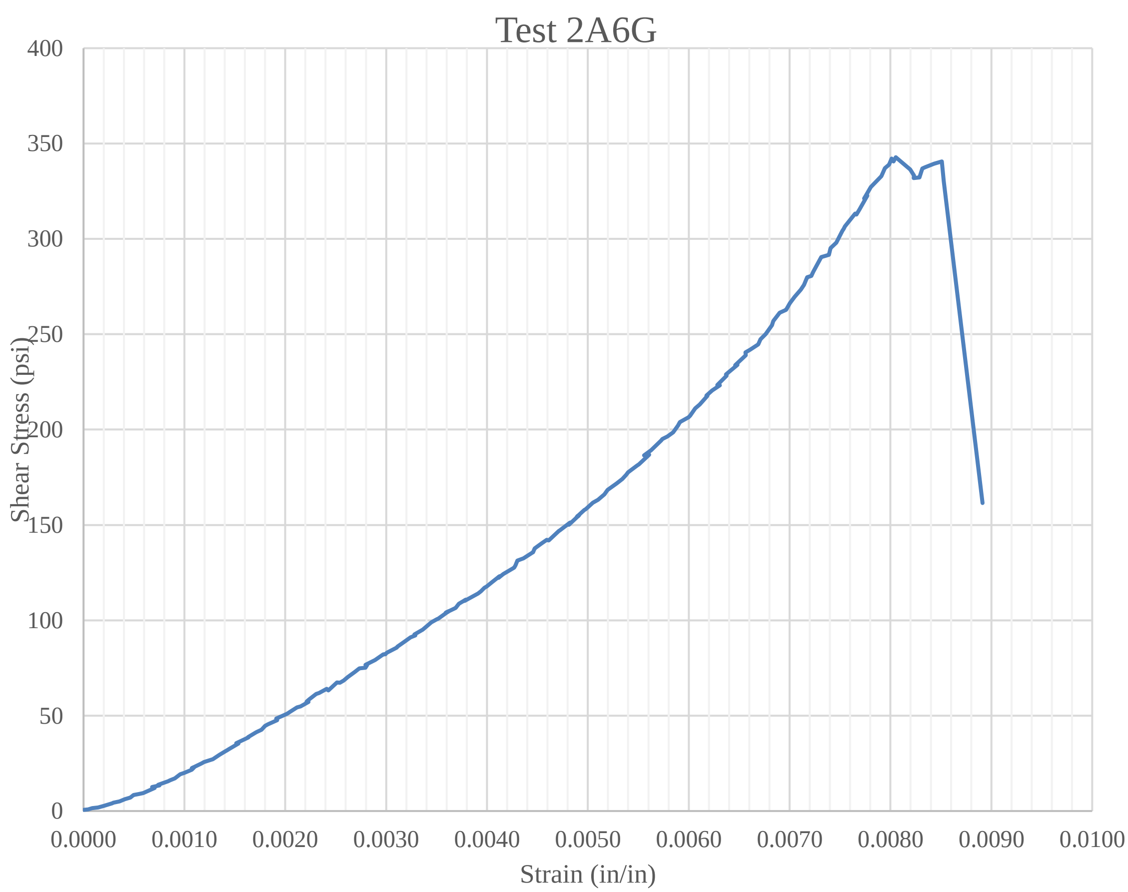


Maximum Load:	4828	lbs
Maximum Stress:	446	psi
Strain at Failure:	0.0093	in/in

DIRECT SHEAR TEST DATA

Test:	Direct Shear (Guillotine) Test	Test Date:	7/11/2016
Slab I.D.:	Slab 2A		
Moisture:	SSD	Tested by:	ASP
Bonding Agent:	Cement Slurry (Wet)		
Core Diameter:	66.7 mm (2 5/8 in)		

SPECIMEN 2A6G



Maximum Load:	3711	lbs
Maximum Stress:	343	psi
Strain at Failure:	0.0081	in/in

DIRECT SHEAR TEST DATA

Test:	Direct Shear (Guillotine) Test	Test Date:	7/11/2016
Slab I.D.:	Slab 2B		
Moisture:	SSD	Tested by:	ASP
Bonding Agent:	Cement Slurry (Dried)		
Core Diameter:	66.7 mm (2 5/8 in)		

SPECIMEN 2B2G

	SI Units		Imperial Units	
Applied Load at Failure	4.6	kN	1023	lbs
Shear Stress at Failure	655	kPa	95	psi

SPECIMEN 2B4G

	SI Units		Imperial Units	
Applied Load at Failure	10.4	kN	2347	lbs
Shear Stress at Failure	1496	kPa	217	psi

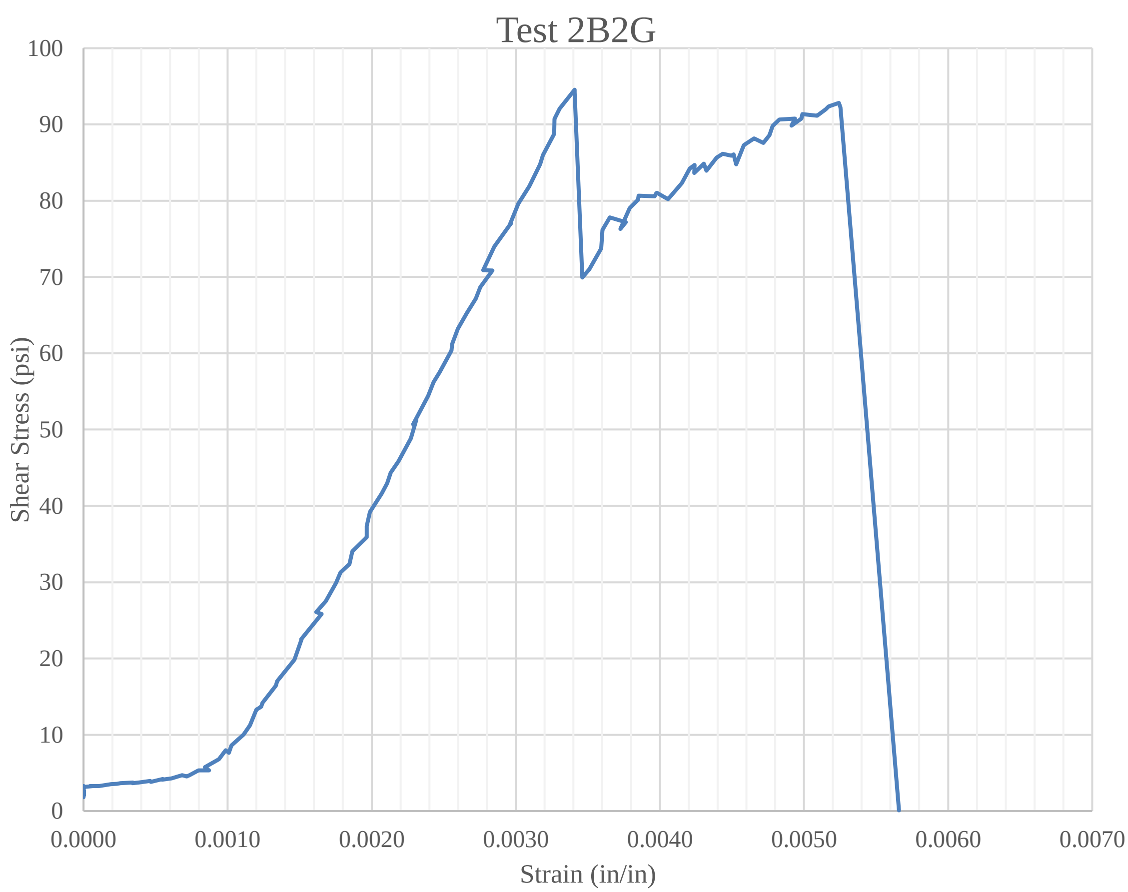
SPECIMEN 2B6G

	SI Units		Imperial Units	
Applied Load at Failure	9.9	kN	2234	lbs
Shear Stress at Failure	1420	kPa	206	psi

DIRECT SHEAR TEST DATA

Test:	Direct Shear (Guillotine) Test	Test Date:	7/11/2016
Slab I.D.:	Slab 2B		
Moisture:	SSD	Tested by:	ASP
Bonding Agent:	Cement Slurry (Dried)		
Core Diameter:	66.7 mm (2 5/8 in)		

SPECIMEN 2B2G

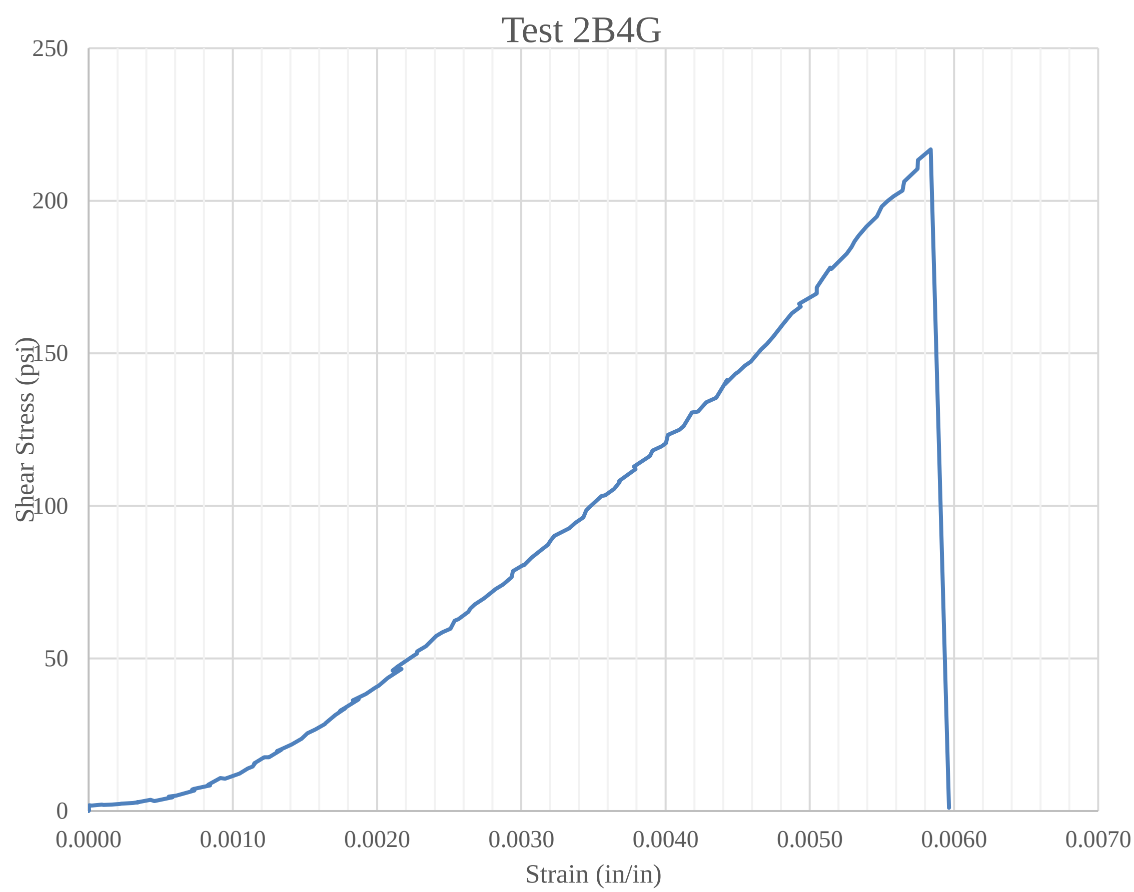


Maximum Load:	1023	lbs
Maximum Stress:	95	psi
Strain at Failure:	0.0034	in/in

DIRECT SHEAR TEST DATA

Test:	Direct Shear (Guillotine) Test	Test Date:	7/11/2016
Slab I.D.:	Slab 2B		
Moisture:	SSD	Tested by:	ASP
Bonding Agent:	Cement Slurry (Dried)		
Core Diameter:	66.7 mm (2 5/8 in)		

SPECIMEN 2B4G

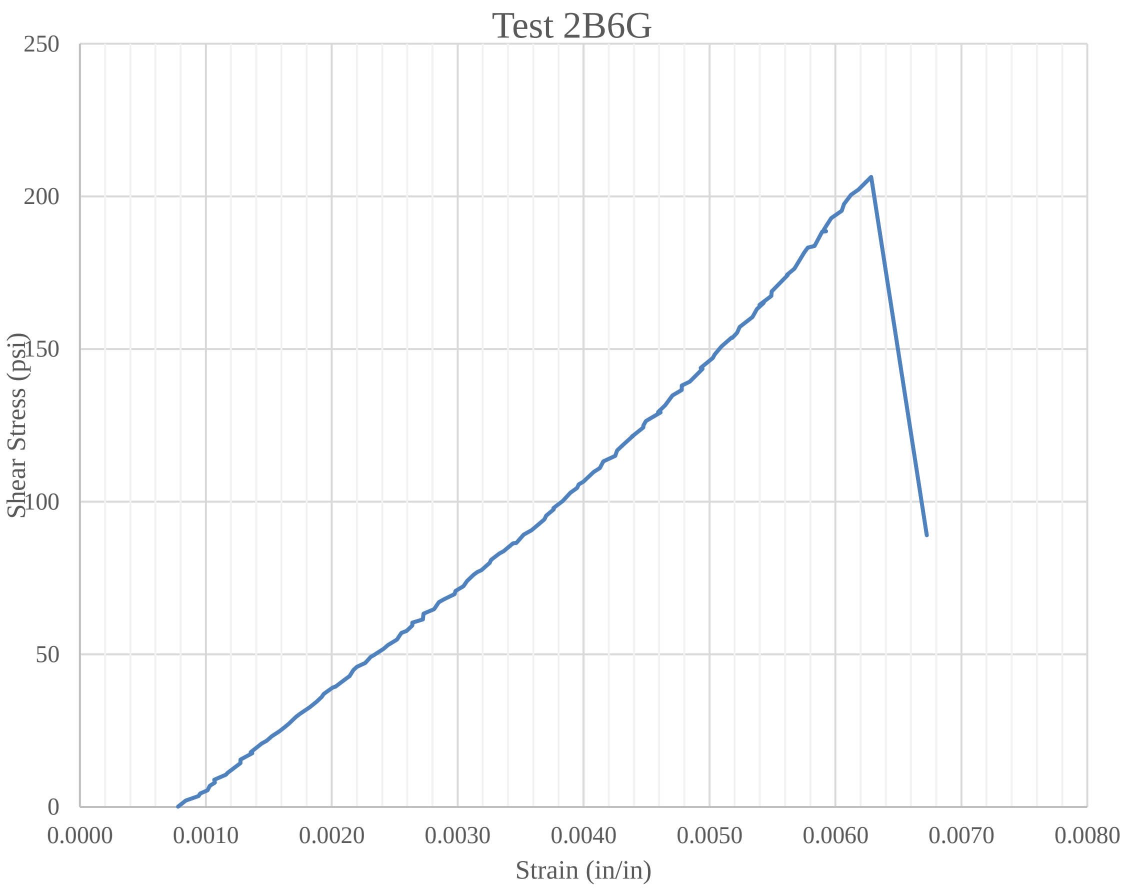


Maximum Load:	2347	lbs
Maximum Stress:	217	psi
Strain at Failure:	0.0058	in/in

DIRECT SHEAR TEST DATA

Test:	Direct Shear (Guillotine) Test	Test Date:	7/11/2016
Slab I.D.:	Slab 2B		
Moisture:	SSD	Tested by:	ASP
Bonding Agent:	Cement Slurry (Dried)		
Core Diameter:	66.7 mm (2 5/8 in)		

SPECIMEN 2B6G



Maximum Load:	2234	lbs
Maximum Stress:	206	psi
Strain at Failure:	0.0063	in/in

DIRECT SHEAR TEST DATA

Test:	Direct Shear (Guillotine) Test	Test Date:	7/11/2016
Slab I.D.:	Slab 3A		
Moisture:	Overwet (small puddles)	Tested by:	ASP
Bonding Agent:	Cement Slurry (Wet)		
Core Diameter:	66.7 mm (2 5/8 in)		

SPECIMEN 3A2G

	SI Units		Imperial Units	
Applied Load at Failure	21.1	kN	4748	lbs
Shear Stress at Failure	3027	kPa	439	psi

SPECIMEN 3A4G

	SI Units		Imperial Units	
Applied Load at Failure	16.3	kN	3658	lbs
Shear Stress at Failure	2330	kPa	338	psi

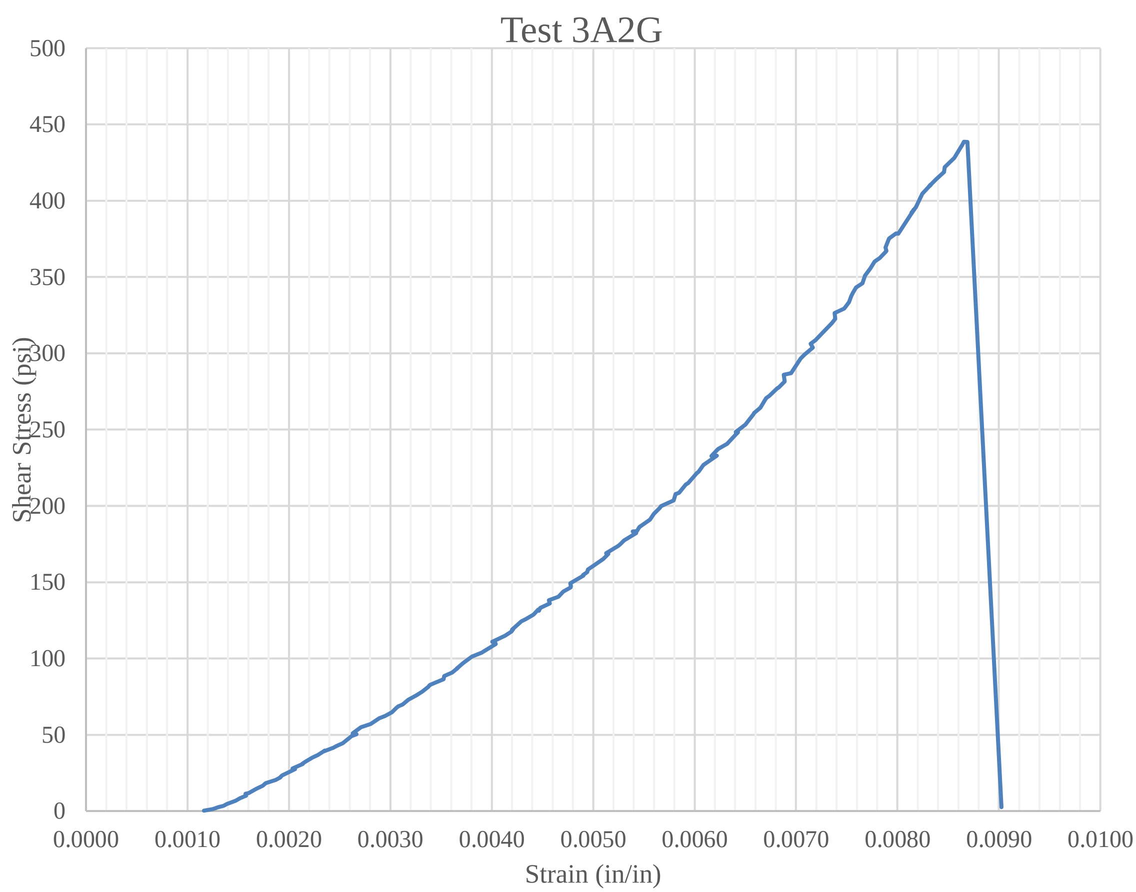
SPECIMEN 3A6G

	SI Units		Imperial Units	
Applied Load at Failure	18.2	kN	4088	lbs
Shear Stress at Failure	2606	kPa	378	psi

DIRECT SHEAR TEST DATA

Test:	Direct Shear (Guillotine) Test	Test Date:	7/11/2016
Slab I.D.:	Slab 3A		
Moisture:	Overwet (small puddles)	Tested by:	ASP
Bonding Agent:	Cement Slurry (Wet)		
Core Diameter:	66.7 mm (2 5/8 in)		

SPECIMEN 3A2G

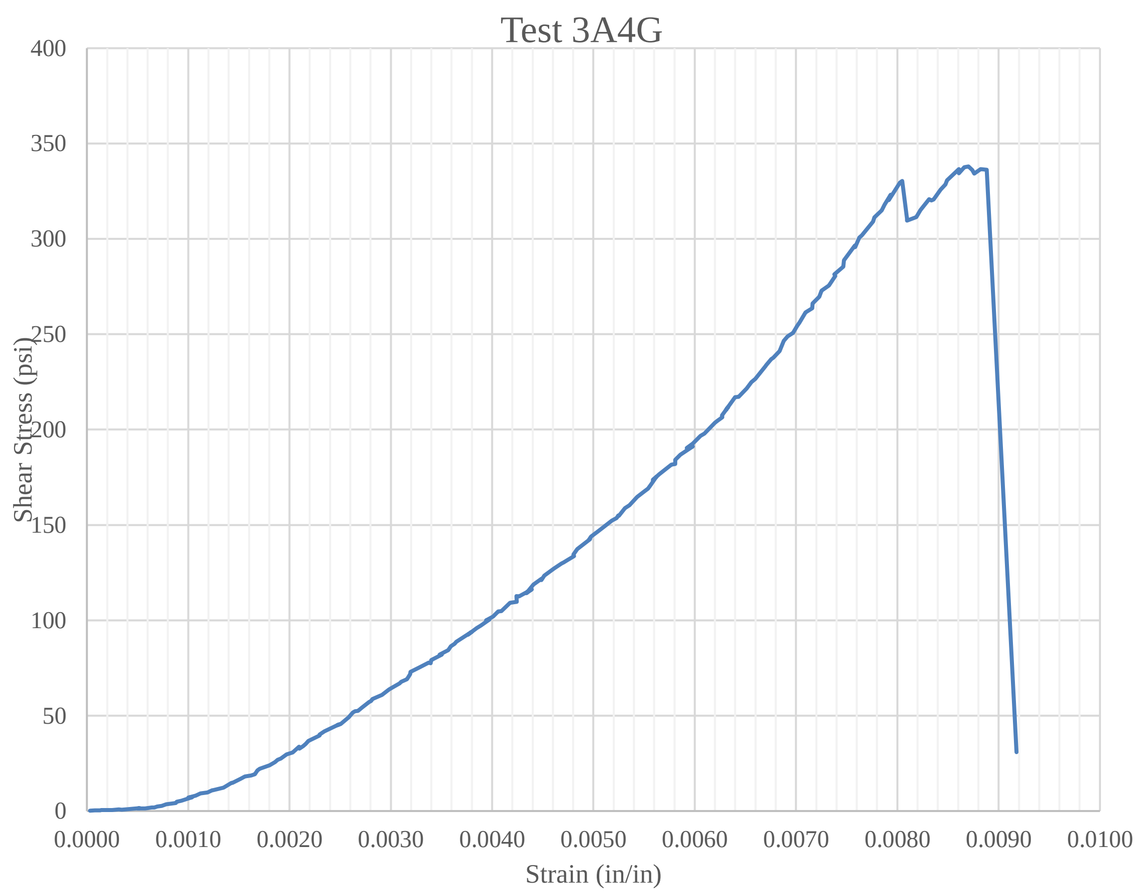


Maximum Load:	4748	lbs
Maximum Stress:	439	psi
Strain at Failure:	0.0087	in/in

DIRECT SHEAR TEST DATA

Test:	Direct Shear (Guillotine) Test	Test Date:	7/11/2016
Slab I.D.:	Slab 3A		
Moisture:	Overwet (small puddles)	Tested by:	ASP
Bonding Agent:	Cement Slurry (Wet)		
Core Diameter:	66.7 mm (2 5/8 in)		

SPECIMEN 3A4G

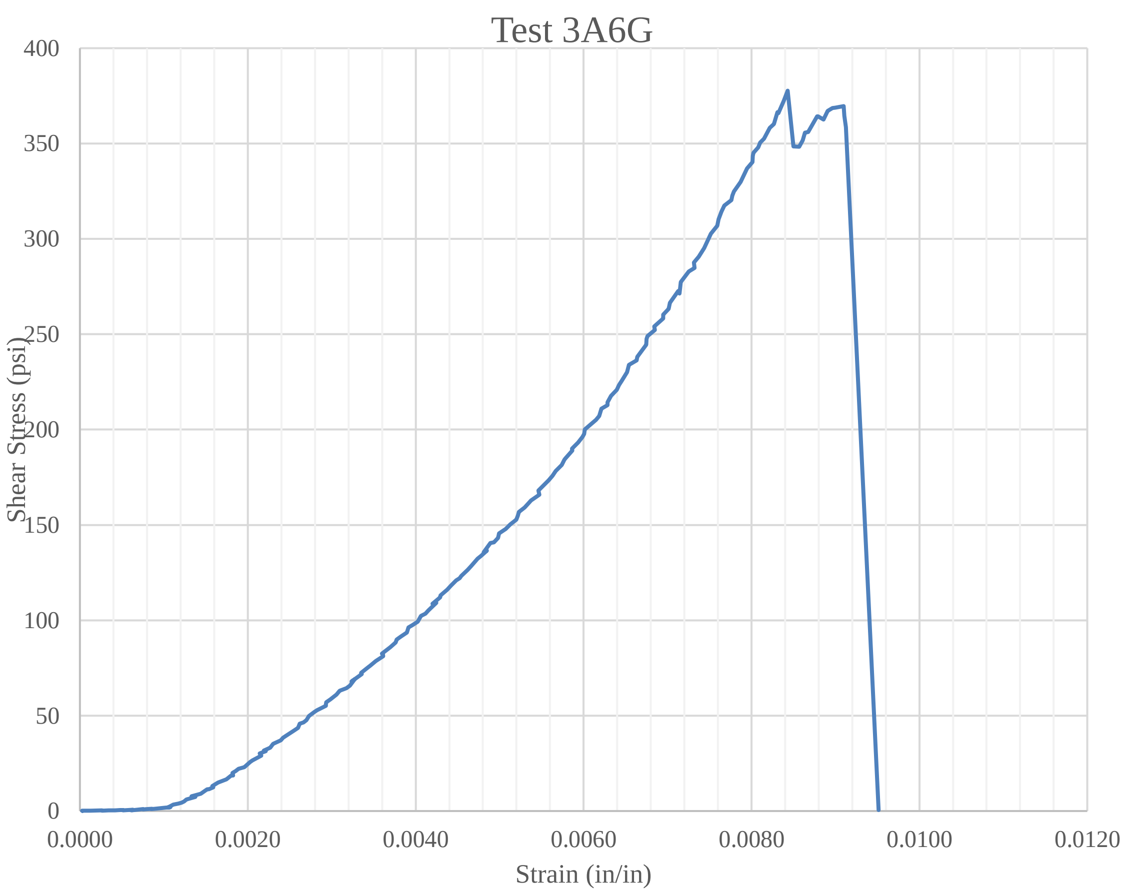


Maximum Load:	3658	lbs
Maximum Stress:	338	psi
Strain at Failure:	0.0087	in/in

DIRECT SHEAR TEST DATA

Test:	Direct Shear (Guillotine) Test	Test Date:	7/11/2016
Slab I.D.:	Slab 3A		
Moisture:	Overwet (small puddles)	Tested by:	ASP
Bonding Agent:	Cement Slurry (Wet)		
Core Diameter:	66.7 mm (2 5/8 in)		

SPECIMEN 3A6G



Maximum Load:	4088	lbs
Maximum Stress:	378	psi
Strain at Failure:	0.0084	in/in

DIRECT SHEAR TEST DATA

Test:	Direct Shear (Guillotine) Test	Test Date:	7/11/2016
Slab I.D.:	Slab 3B		
Moisture:	SSD	Tested by:	ASP
Bonding Agent:	None		
Core Diameter:	66.7 mm (2 5/8 in)		

SPECIMEN 3B2G

	SI Units		Imperial Units	
Applied Load at Failure	18.7	kN	4205	lbs
Shear Stress at Failure	2675	kPa	388	psi

SPECIMEN 3B4G

	SI Units		Imperial Units	
Applied Load at Failure	19.1	kN	4290	lbs
Shear Stress at Failure	2730	kPa	396	psi

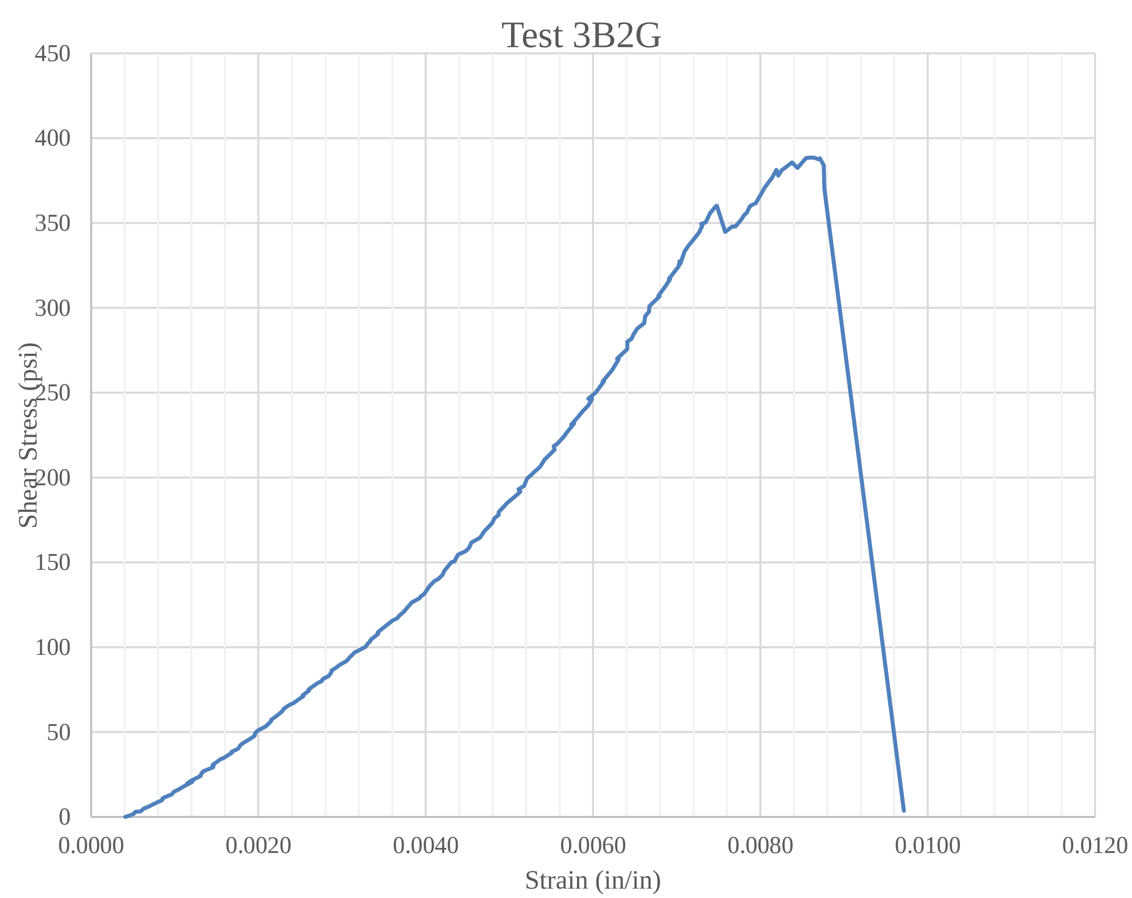
SPECIMEN 3B6G

	SI Units		Imperial Units	
Applied Load at Failure	22.3	kN	5007	lbs
Shear Stress at Failure	3192	kPa	463	psi

DIRECT SHEAR TEST DATA

Test:	Direct Shear (Guillotine) Test	Test Date:	7/11/2016
Slab I.D.:	Slab 3B		
Moisture:	SSD	Tested by:	ASP
Bonding Agent:	None		
Core Diameter:	66.7 mm (2 5/8 in)		

SPECIMEN 3B2G

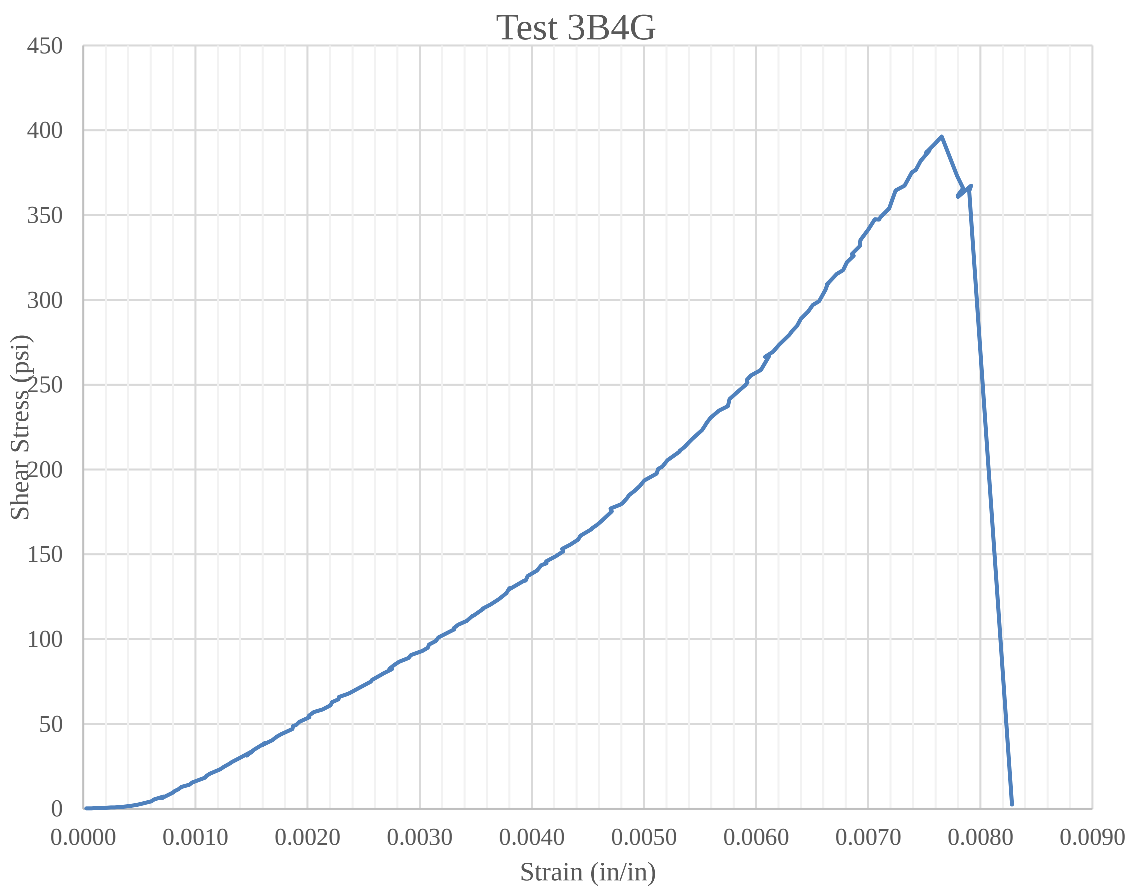


Maximum Load:	4205	lbs
Maximum Stress:	388	psi
Strain at Failure:	0.0086	in/in

DIRECT SHEAR TEST DATA

Test:	Direct Shear (Guillotine) Test	Test Date:	7/11/2016
Slab I.D.:	Slab 3B		
Moisture:	SSD	Tested by:	ASP
Bonding Agent:	None		
Core Diameter:	66.7 mm (2 5/8 in)		

SPECIMEN 3B4G

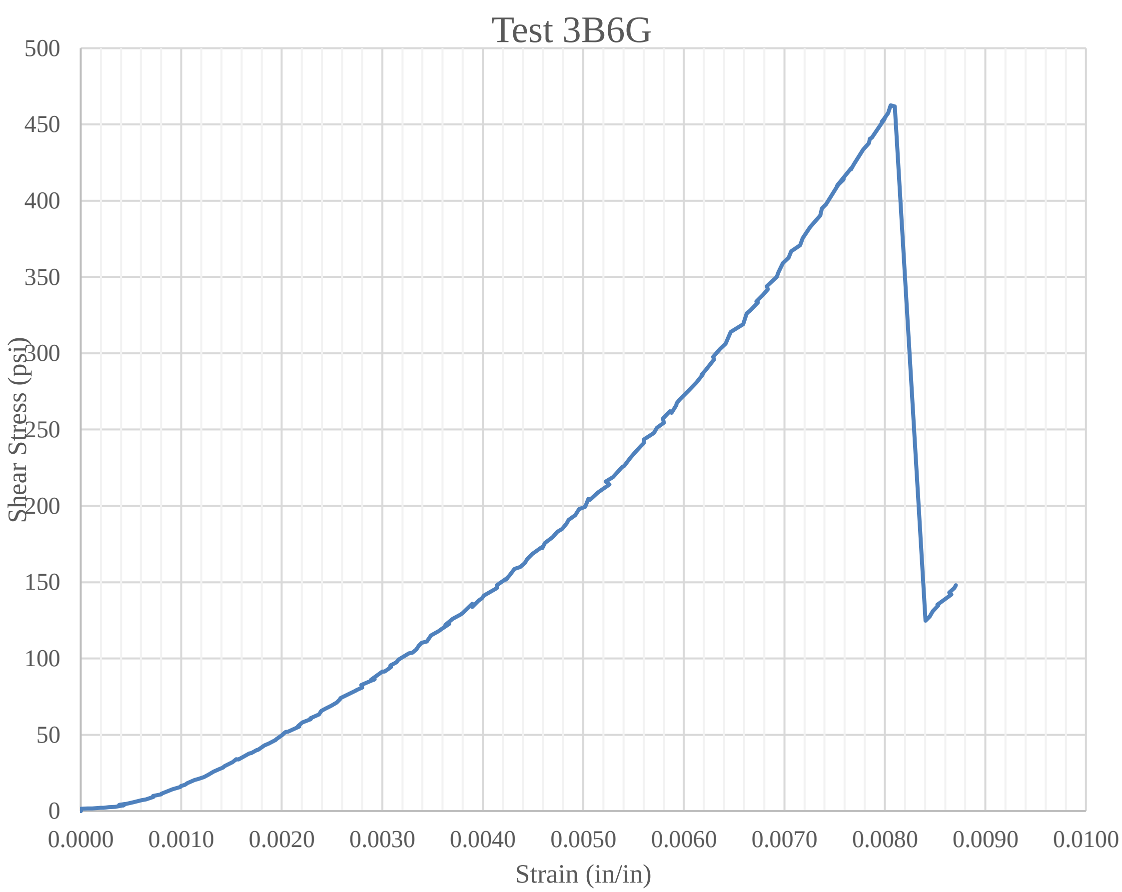


Maximum Load:	4290	lbs
Maximum Stress:	396	psi
Strain at Failure:	0.0077	in/in

DIRECT SHEAR TEST DATA

Test:	Direct Shear (Guillotine) Test	Test Date:	7/11/2016
Slab I.D.:	Slab 3B		
Moisture:	SSD	Tested by:	ASP
Bonding Agent:	None		
Core Diameter:	66.7 mm (2 5/8 in)		

SPECIMEN 3B6G



Maximum Load:	5007	lbs
Maximum Stress:	463	psi
Strain at Failure:	0.0081	in/in

APPENDIX C

SLANT SHEAR TEST DATA

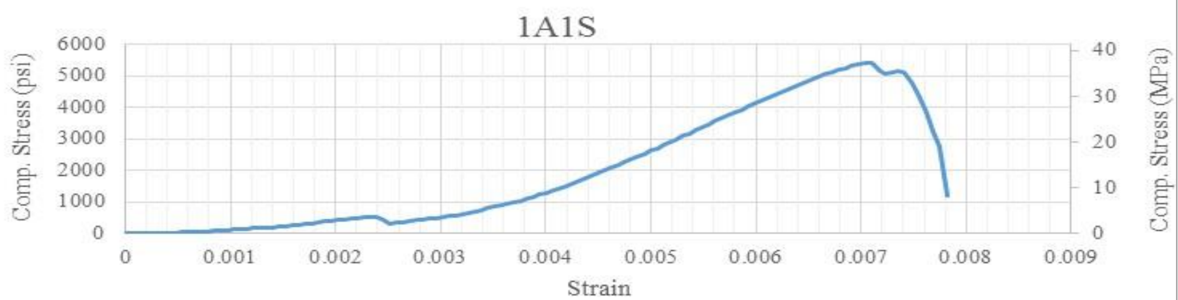
Appendix C contains recorded data from the slant shear tests. Specimens are grouped by slab number. The maximum compressive force applied, measured using the MTS equipment, is given for each specimen. The shear stress at failure is calculated as the transformed shearing stress on the slanted interface based on the applied uniaxial compression force. The stress-strain plot is based on the recorded load-displacement data, converted to compressive stress and strain using the area of the specimen and the original specimen length, respectively.

SLANT SHEAR TEST DATA

Test:	Slant Shear Test	Test Date:	8/1/2016
Slab I.D.:	Slab 1A		
Moisture:	Dry	Tested by:	ASP
Bonding Agent:	None		
Core Diameter:	66.7 mm (2 5/8 in)	Slant Angle:	45 degrees

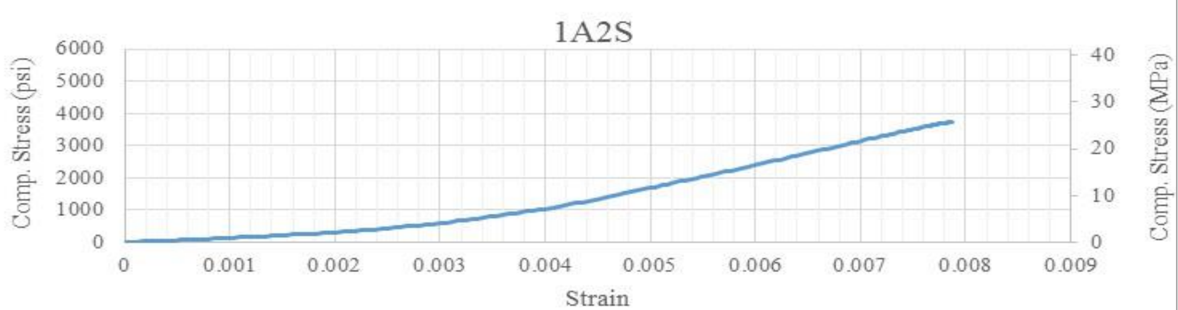
SPECIMEN 1A1S

	SI Units		Imperial Units	
Applied Load at Failure	131	kN	29360	lbs
Comp. Stress at Failure	37.4	MPa	5425	psi
Shear Stress at Interface at Failure	18706	kPa	2713	psi



SPECIMEN 1A2S

	SI Units		Imperial Units	
Applied Load at Failure	89.7	kN	20148	lbs
Comp. Stress at Failure	25.7	MPa	3723	psi
Shear Stress at Interface at Failure	12831	kPa	1861	psi

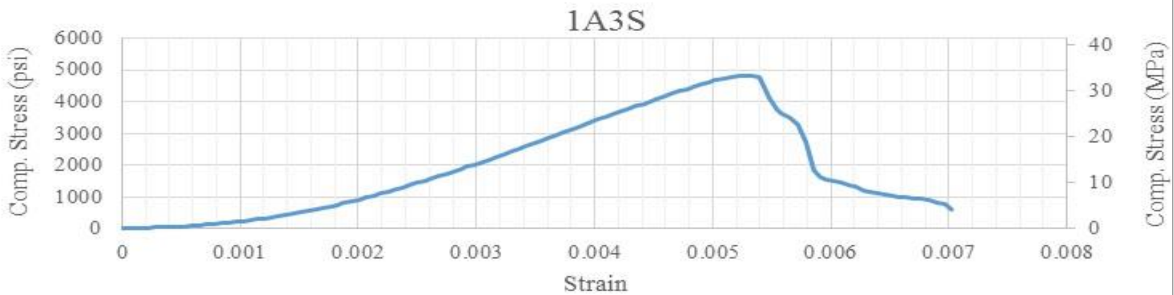


SLANT SHEAR TEST DATA

Test:	Slant Shear Test	Test Date:	8/1/2016
Slab I.D.:	Slab 1A		
Moisture:	Dry	Tested by:	ASP
Bonding Agent:	None		
Core Diameter:	66.7 mm (2 5/8 in)	Slant Angle:	45 degrees

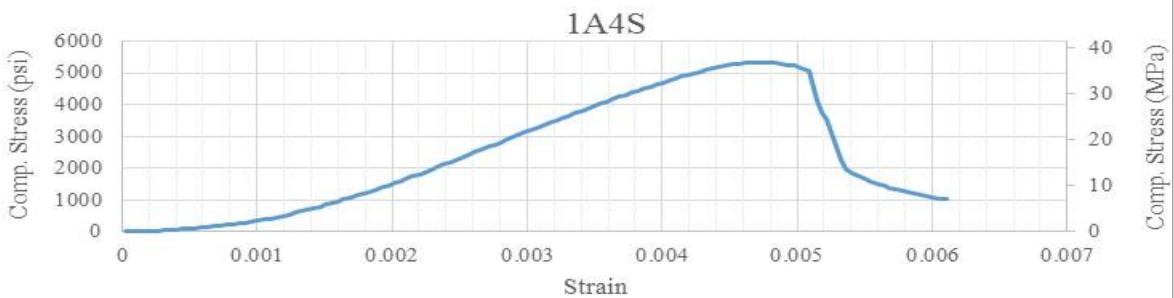
SPECIMEN 1A3S

	SI Units		Imperial Units	
Applied Load at Failure	116	kN	26075	lbs
Comp. Stress at Failure	33.2	MPa	4818	psi
Shear Stress at Interface at Failure	16610	kPa	2409	psi



SPECIMEN 1A4S

	SI Units		Imperial Units	
Applied Load at Failure	129	kN	28928	lbs
Comp. Stress at Failure	36.9	MPa	5345	psi
Shear Stress at Interface at Failure	18430	kPa	2673	psi

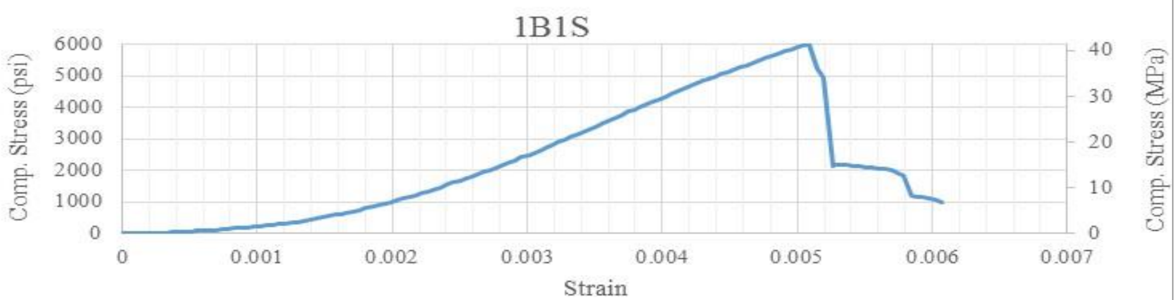


SLANT SHEAR TEST DATA

Test:	Slant Shear Test	Test Date:	8/1/2016
Slab I.D.:	Slab 1B		
Moisture:	Dry	Tested by:	ASP
Bonding Agent:	Cement Slurry (Wet)		
Core Diameter:	66.7 mm (2 5/8 in)	Slant Angle:	45 degrees

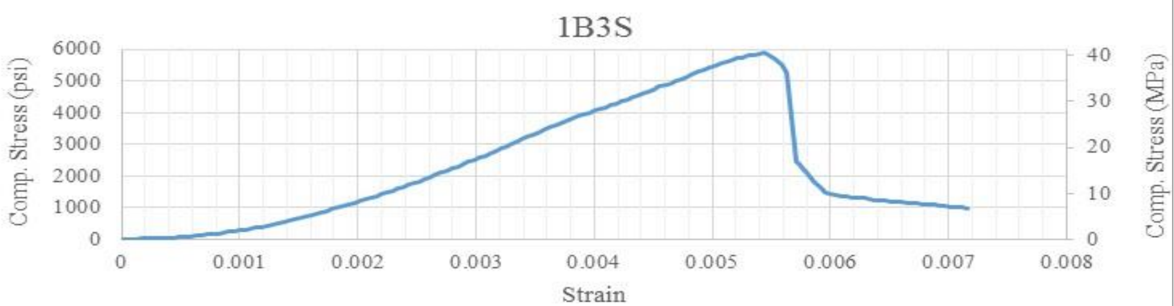
SPECIMEN 1B1S

	SI Units		Imperial Units	
Applied Load at Failure	144	kN	32448	lbs
Comp. Stress at Failure	41.3	MPa	5996	psi
Shear Stress at Interface at Failure	20671	kPa	2998	psi



SPECIMEN 1B3S

	SI Units		Imperial Units	
Applied Load at Failure	142	kN	31848	lbs
Comp. Stress at Failure	40.6	MPa	5885	psi
Shear Stress at Interface at Failure	20284	kPa	2942	psi

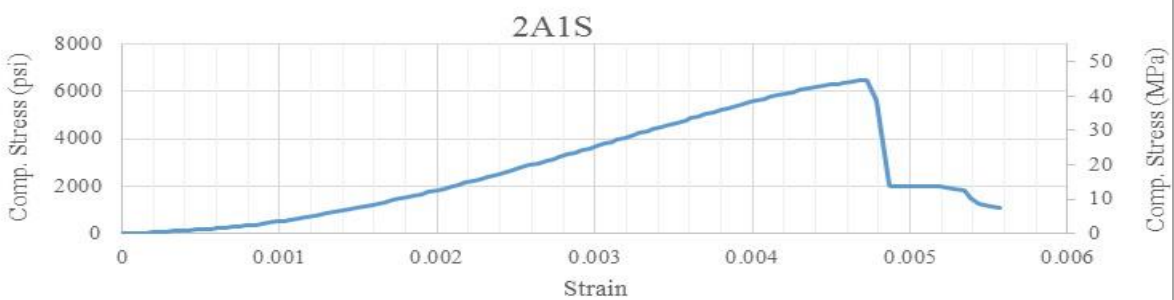


SLANT SHEAR TEST DATA

Test:	Slant Shear Test	Test Date:	8/1/2016
Slab I.D.:	Slab 2A		
Moisture:	SSD	Tested by:	ASP
Bonding Agent:	Cement Slurry (Wet)		
Core Diameter:	66.7 mm (2 5/8 in)	Slant Angle:	45 degrees

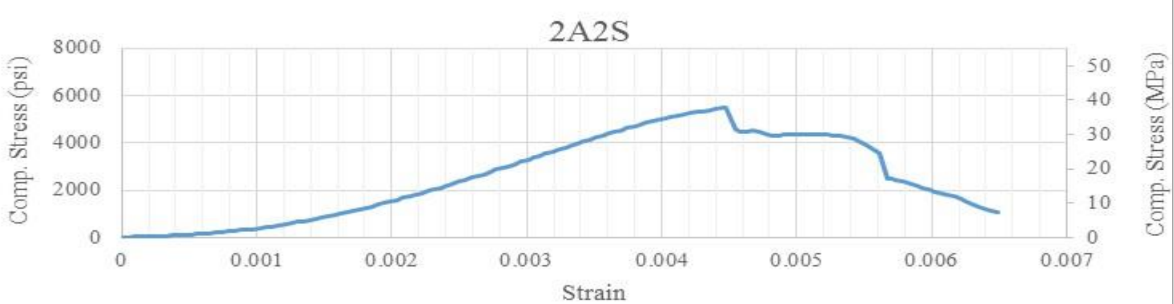
SPECIMEN 2A1S

	SI Units		Imperial Units	
Applied Load at Failure	156	kN	35122	lbs
Comp. Stress at Failure	44.7	MPa	6490	psi
Shear Stress at Interface at Failure	22374	kPa	3245	psi



SPECIMEN 2A2S

	SI Units		Imperial Units	
Applied Load at Failure	132	kN	29586	lbs
Comp. Stress at Failure	37.7	MPa	5467	psi
Shear Stress at Interface at Failure	18843	kPa	2733	psi

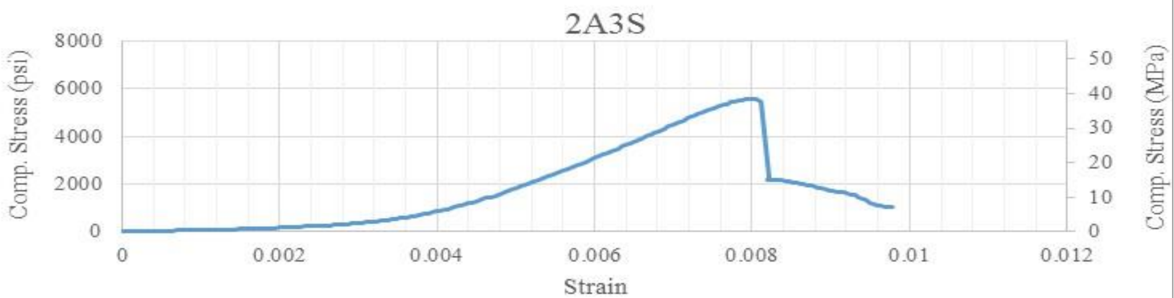


SLANT SHEAR TEST DATA

Test:	Slant Shear Test	Test Date:	8/1/2016
Slab I.D.:	Slab 2A		
Moisture:	SSD	Tested by:	ASP
Bonding Agent:	Cement Slurry (Wet)		
Core Diameter:	66.7 mm (2 5/8 in)	Slant Angle:	45 degrees

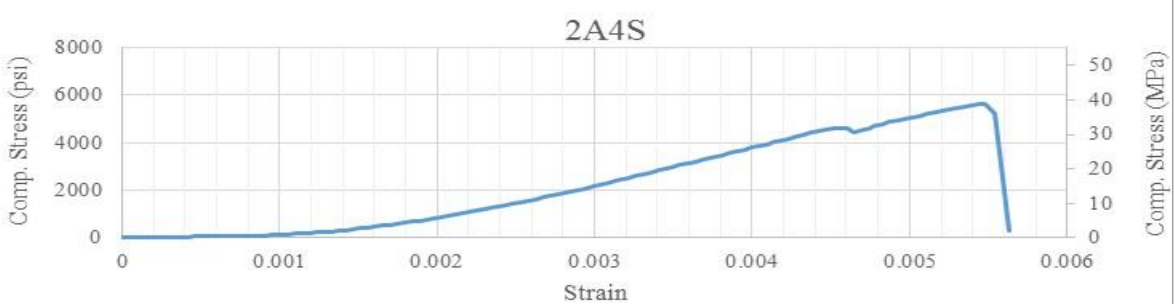
SPECIMEN 2A3S

	SI Units		Imperial Units	
Applied Load at Failure	135	kN	30215	lbs
Comp. Stress at Failure	38.5	MPa	5583	psi
Shear Stress at Interface at Failure	19250	kPa	2792	psi



SPECIMEN 2A4S

	SI Units		Imperial Units	
Applied Load at Failure	135	kN	30429	lbs
Comp. Stress at Failure	38.8	MPa	5623	psi
Shear Stress at Interface at Failure	19381	kPa	2811	psi

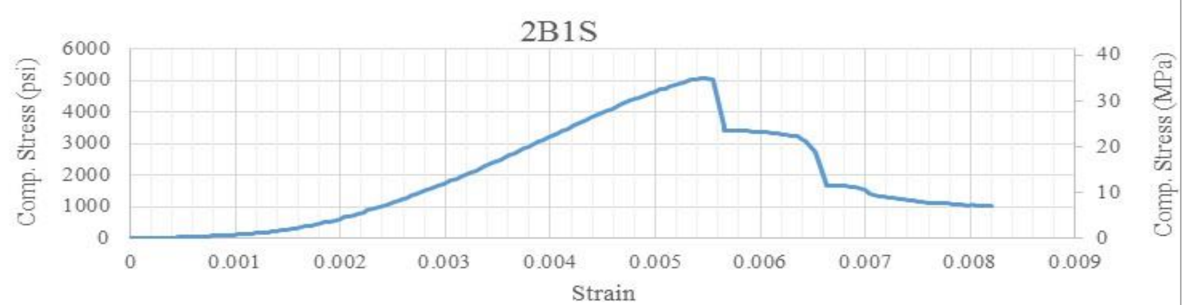


SLANT SHEAR TEST DATA

Test:	Slant Shear Test	Test Date:	8/1/2016
Slab I.D.:	Slab 2B		
Moisture:	SSD	Tested by:	ASP
Bonding Agent:	Cement Slurry (Dried)		
Core Diameter:	66.7 mm (2 5/8 in)	Slant Angle:	45 degrees

SPECIMEN 2B1S

	SI Units		Imperial Units	
Applied Load at Failure	122	kN	27481	lbs
Comp. Stress at Failure	35.0	MPa	5078	psi
Shear Stress at Interface at Failure	17506	kPa	2539	psi

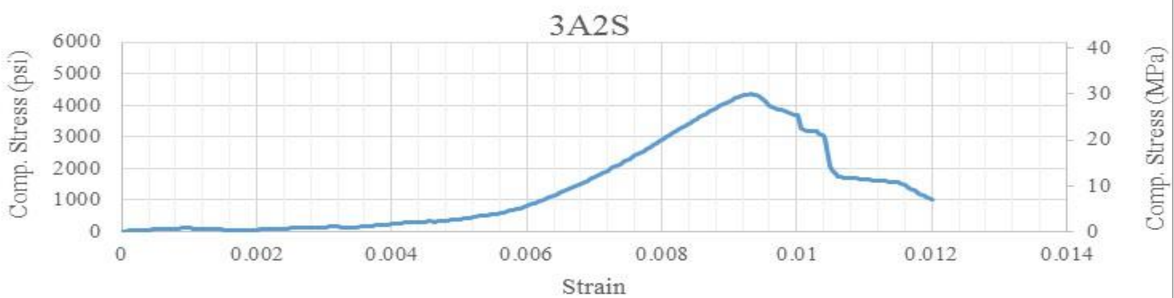


SLANT SHEAR TEST DATA

Test:	Slant Shear Test	Test Date:	8/1/2016
Slab I.D.:	Slab 3A		
Moisture:	Overwet (small puddles)	Tested by:	ASP
Bonding Agent:	Cement Slurry (Wet)		
Core Diameter:	66.7 mm (2 5/8 in)	Slant Angle:	45 degrees

SPECIMEN 3A2S

	SI Units		Imperial Units	
Applied Load at Failure	105	kN	23529	lbs
Comp. Stress at Failure	30.0	MPa	4348	psi
Shear Stress at Interface at Failure	14989	kPa	2174	psi

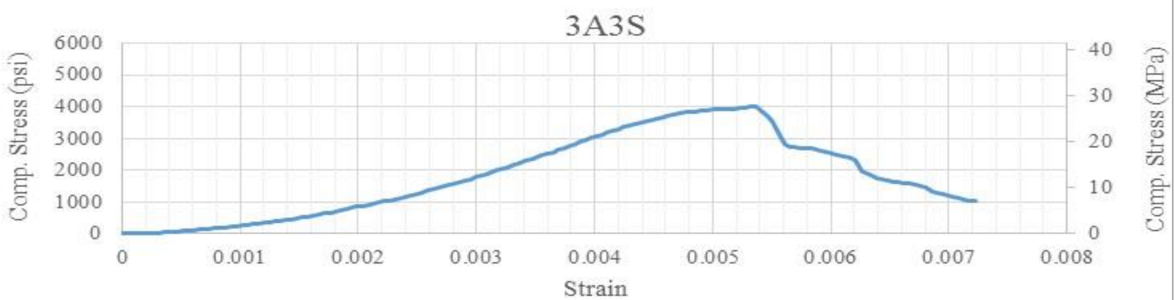


SLANT SHEAR TEST DATA

Test:	Slant Shear Test	Test Date:	8/1/2016
Slab I.D.:	Slab 3A		
Moisture:	Overwet (small puddles)	Tested by:	ASP
Bonding Agent:	Cement Slurry (Wet)		
Core Diameter:	66.7 mm (2 5/8 in)	Slant Angle:	45 degrees

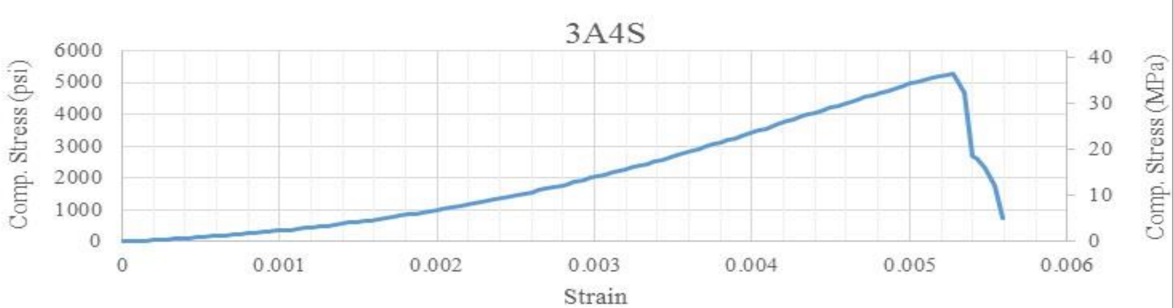
SPECIMEN 3A3S

	SI Units		Imperial Units	
Applied Load at Failure	96.4	kN	21657	lbs
Comp. Stress at Failure	27.6	MPa	4002	psi
Shear Stress at Interface at Failure	13796	kPa	2001	psi



SPECIMEN 3A4S

	SI Units		Imperial Units	
Applied Load at Failure	127	kN	28559	lbs
Comp. Stress at Failure	36.4	MPa	5277	psi
Shear Stress at Interface at Failure	18195	kPa	2639	psi

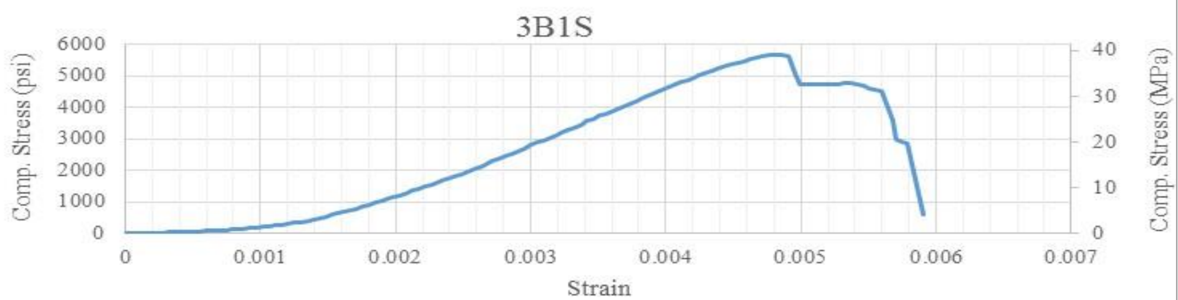


SLANT SHEAR TEST DATA

Test:	Slant Shear Test	Test Date:	8/1/2016
Slab I.D.:	Slab 3B		
Moisture:	SSD	Tested by:	ASP
Bonding Agent:	None		
Core Diameter:	66.7 mm (2 5/8 in)	Slant Angle:	45 degrees

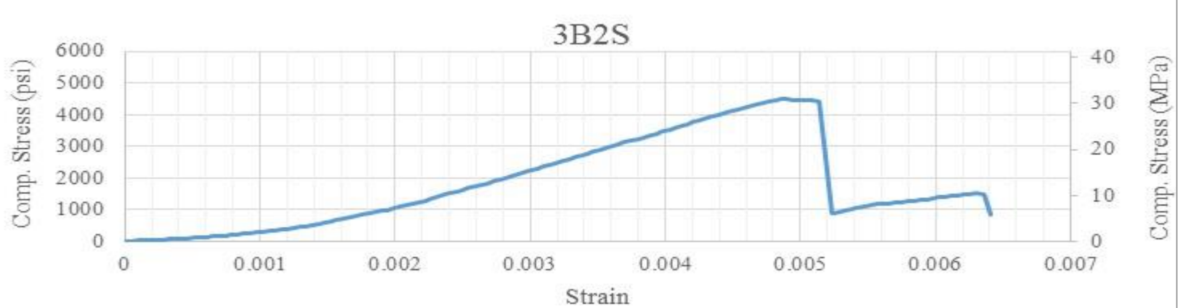
SPECIMEN 3B1S

	SI Units		Imperial Units	
Applied Load at Failure	136	kN	30659	lbs
Comp. Stress at Failure	39.1	MPa	5665	psi
Shear Stress at Interface at Failure	19533	kPa	2833	psi



SPECIMEN 3B2S

	SI Units		Imperial Units	
Applied Load at Failure	108	kN	24272	lbs
Comp. Stress at Failure	30.9	MPa	4485	psi
Shear Stress at Interface at Failure	15458	kPa	2242	psi

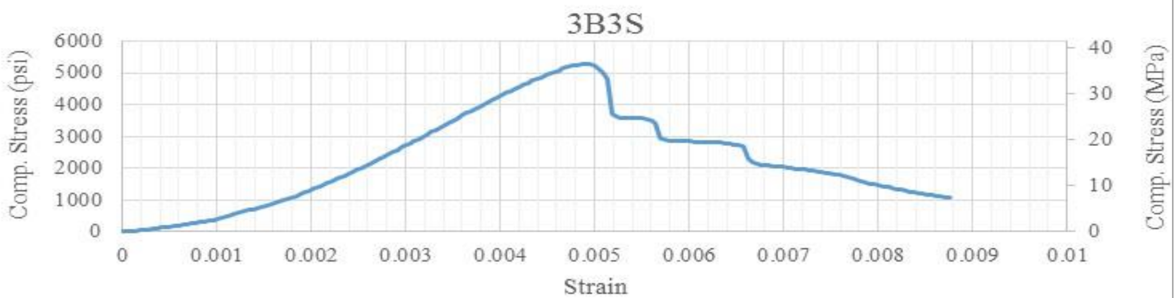


SLANT SHEAR TEST DATA

Test:	Slant Shear Test	Test Date:	8/1/2016
Slab I.D.:	Slab 3B		
Moisture:	SSD	Tested by:	ASP
Bonding Agent:	None		
Core Diameter:	66.7 mm (2 5/8 in)	Slant Angle:	45 degrees

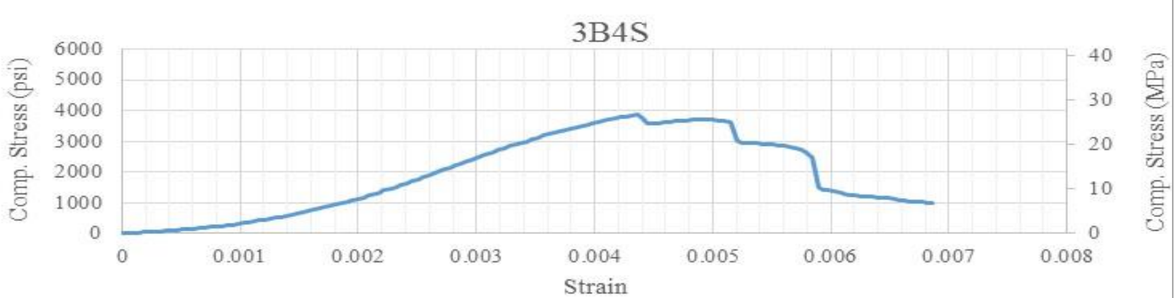
SPECIMEN 3B3S

	SI Units		Imperial Units	
Applied Load at Failure	127	kN	28609	lbs
Comp. Stress at Failure	36.4	MPa	5286	psi
Shear Stress at Interface at Failure	18223	kPa	2643	psi



SPECIMEN 3B4S

	SI Units		Imperial Units	
Applied Load at Failure	93.0	kN	20909	lbs
Comp. Stress at Failure	26.6	MPa	3864	psi
Shear Stress at Interface at Failure	13321	kPa	1932	psi



APPENDIX D

JACKING TEST DATA

Appendix D contains recorded data from the jacking tests. Specimens are grouped by slab number. The maximum shearing force applied, measured using the Simplex hydraulic jack, is given for each specimen. The shear stress at failure is calculated based on the recorded shearing force and gross bonded area.

JACKING TEST DATA

Test:	Jacking Test	Test Date:	8/13/2016
Slab I.D.:	Slab 1A		
Moisture:	Dry	Tested by:	ASP
Bonding Agent:	None		
Jack Area:	4154 mm^2 (6.44 in^2)		

SPECIMEN 1A1J

	SI Units		Imperial Units	
Length	130	mm	5 1/8	in
Width	143	mm	5 5/8	in
Applied Load at Failure	19.2	kN	4315	lbs
Shear Stress at Failure	1032	kPa	150	psi

SPECIMEN 1A2J

	SI Units		Imperial Units	
Length	133	mm	5 1/4	in
Width	152	mm	6	in
Applied Load at Failure	23.5	kN	5281	lbs
Shear Stress at Failure	1156	kPa	168	psi

SPECIMEN 1A3J

	SI Units		Imperial Units	
Length	140	mm	5 1/2	in
Width	143	mm	5 5/8	in
Applied Load at Failure	26.4	kN	5925	lbs
Shear Stress at Failure	1320	kPa	192	psi

SPECIMEN 1A4J

	SI Units		Imperial Units	
Length	140	mm	5 1/2	in
Width	152	mm	6	in
Applied Load at Failure	20.5	kN	4605	lbs
Shear Stress at Failure	962	kPa	140	psi

JACKING TEST DATA

Test:	Jacking Test	Test Date:	8/13/2016
Slab I.D.:	Slab 1B		
Moisture:	Dry	Tested by:	ASP
Bonding Agent:	Cement Slurry (Wet)		
Jack Area:	4154 mm^2 (6.44 in^2)		

SPECIMEN 1B1J

	SI Units		Imperial Units	
Length	146	mm	5 3/4	in
Width	149	mm	5 7/8	in
Applied Load at Failure	26.4	kN	5925	lbs
Shear Stress at Failure	1209	kPa	175	psi

SPECIMEN 1B2J

	SI Units		Imperial Units	
Length	146	mm	5 3/4	in
Width	165	mm	6 1/2	in
Applied Load at Failure	31.5	kN	7084	lbs
Shear Stress at Failure	1307	kPa	190	psi

SPECIMEN 1B3J

	SI Units		Imperial Units	
Length	146	mm	5 3/4	in
Width	133	mm	5 1/4	in
Applied Load at Failure	23.5	kN	5281	lbs
Shear Stress at Failure	1206	kPa	175	psi

SPECIMEN 1B4J

	SI Units		Imperial Units	
Length	146	mm	5 3/4	in
Width	146	mm	5 3/4	in
Applied Load at Failure	22.1	kN	4959	lbs
Shear Stress at Failure	1034	kPa	150	psi

JACKING TEST DATA

Test:	Jacking Test	Test Date:	8/13/2016
Slab I.D.:	Slab 2A		
Moisture:	SSD	Tested by:	ASP
Bonding Agent:	Cement Slurry (Wet)		
Jack Area:	4154 mm^2 (6.44 in^2)		

SPECIMEN 2A1J

	SI Units		Imperial Units	
Length	146	mm	5 3/4	in
Width	83	mm	3 1/4	in
Applied Load at Failure	20.9	kN	4701	lbs
Shear Stress at Failure	1734	kPa	252	psi

SPECIMEN 2A2J

	SI Units		Imperial Units	
Length	146	mm	5 3/4	in
Width	152	mm	6	in
Applied Load at Failure	31.0	kN	6955	lbs
Shear Stress at Failure	1390	kPa	202	psi

SPECIMEN 2A3J

	SI Units		Imperial Units	
Length	143	mm	5 5/8	in
Width	133	mm	5 1/4	in
Applied Load at Failure	29.4	kN	6601	lbs
Shear Stress at Failure	1541	kPa	224	psi

SPECIMEN 2A4J

	SI Units		Imperial Units	
Length	143	mm	5 5/8	in
Width	133	mm	5 1/4	in
Applied Load at Failure	32.7	kN	7342	lbs
Shear Stress at Failure	1714	kPa	249	psi

JACKING TEST DATA

Test:	Jacking Test	Test Date:	8/13/2016
Slab I.D.:	Slab 2B		
Moisture:	Dry	Tested by:	ASP
Bonding Agent:	Cement Slurry (Dried)		
Jack Area:	4154 mm^2 (6.44 in^2)		

SPECIMEN 2B1J

	SI Units		Imperial Units	
Length	149	mm	5 7/8	in
Width	156	mm	6 1/8	in
Applied Load at Failure	19.1	kN	4283	lbs
Shear Stress at Failure	820	kPa	119	psi

SPECIMEN 2B2J

	SI Units		Imperial Units	
Length	152	mm	6	in
Width	152	mm	6	in
Applied Load at Failure	19.2	kN	4315	lbs
Shear Stress at Failure	827	kPa	120	psi

SPECIMEN 2B3J

	SI Units		Imperial Units	
Length	152	mm	6	in
Width	137	mm	5 3/8	in
Applied Load at Failure	22.5	kN	5055	lbs
Shear Stress at Failure	1081	kPa	157	psi

SPECIMEN 2B4J

	SI Units		Imperial Units	
Length	152	mm	6	in
Width	140	mm	5 1/2	in
Applied Load at Failure	23.8	kN	5345	lbs
Shear Stress at Failure	1117	kPa	162	psi

JACKING TEST DATA

Test:	Jacking Test	Test Date:	8/13/2016
Slab I.D.:	Slab 3A		
Moisture:	Overwet (small puddles)	Tested by:	ASP
Bonding Agent:	Cement Slurry (Wet)		
Jack Area:	4154 mm^2 (6.44 in^2)		

SPECIMEN 3A1J

	SI Units		Imperial Units	
Length	159	mm	6 1/4	in
Width	108	mm	4 1/4	in
Applied Load at Failure	25.7	kN	5764	lbs
Shear Stress at Failure	1496	kPa	217	psi

SPECIMEN 3A2J

	SI Units		Imperial Units	
Length	159	mm	6 1/4	in
Width	108	mm	4 1/4	in
Applied Load at Failure	29.2	kN	6569	lbs
Shear Stress at Failure	1705	kPa	247	psi

SPECIMEN 3A3J

	SI Units		Imperial Units	
Length	162	mm	6 3/8	in
Width	130	mm	5 1/8	in
Applied Load at Failure	31.8	kN	7148	lbs
Shear Stress at Failure	1509	kPa	219	psi

SPECIMEN 3A4J

	SI Units		Imperial Units	
Length	162	mm	6 3/8	in
Width	140	mm	5 1/2	in
Applied Load at Failure	30.1	kN	6762	lbs
Shear Stress at Failure	1330	kPa	193	psi

JACKING TEST DATA

Test:	Jacking Test	Test Date:	8/13/2016
Slab I.D.:	Slab 3B		
Moisture:	SSD	Tested by:	ASP
Bonding Agent:	None		
Jack Area:	4154 mm^2 (6.44 in^2)		

SPECIMEN 3B1J

	SI Units		Imperial Units	
Length	152	mm	6	in
Width	159	mm	6 1/4	in
Applied Load at Failure	28.7	kN	6440	lbs
Shear Stress at Failure	1182	kPa	172	psi

SPECIMEN 3B2J

	SI Units		Imperial Units	
Length	156	mm	6 1/8	in
Width	152	mm	6	in
Applied Load at Failure	37.3	kN	8372	lbs
Shear Stress at Failure	1571	kPa	228	psi

SPECIMEN 3B3J

	SI Units		Imperial Units	
Length	159	mm	6 1/4	in
Width	130	mm	5 1/8	in
Applied Load at Failure	38.7	kN	8694	lbs
Shear Stress at Failure	1871	kPa	271	psi

SPECIMEN 3B4J

	SI Units		Imperial Units	
Length	159	mm	6 1/4	in
Width	130	mm	5 1/8	in
Applied Load at Failure	31.5	kN	7084	lbs
Shear Stress at Failure	1525	kPa	221	psi

APPENDIX E

SLANT SHEAR DISCUSSION

E.1 The Effects of Slant Angle 'α' on the Transformed Stresses

The slant shear test exerts a combination of compression and shear on the bonded surface resulting from the angle of inclination of the surface. The compression force can be resolved into two components: a compression stress 'σ_N' normal to the bond surface, known as clamping force, and shearing stress 'τ_{NT}' parallel to the bond surface (Figure E-1). In a roughened surface, the clamping force amplifies the effect of mechanical interlock, in turn greatly increasing the observed failure stress at the bond surface. Austin, et al. (1999) plotted the ratio of applied compression stress to applied shear on the bond surface using experimentally determined coefficients of friction for three types of surfaces: smooth, medium rough, and rough. The coefficients used were 0.75, 1.0, and 1.25, respectively. The shear stress experienced by the bond (c_{bond}) is determined via Equation (E-1), where τ_{nt} represents the transformed shear stress on the bond surface, μ represents the friction coefficient, and σ_{nn} represents the transformed normal stress. The shear stress on the bond is then divided by σ_0 (the applied compressive stress on the sample); the resulting ratio is therefore independent of the magnitude of the applied compressive stress.

$$c_{bond} = \tau_{nt} - \mu\sigma_{nn} \qquad \text{(E-1)}$$

Figure E-2 plots the ratio c_{bond}/σ_0 for the representative roughnesses proposed by Austin, et al (1999). This graph indicates that, for a smooth surface, the optimal slant angle (the angle that is mostly likely to produce a slip failure in shear) is between 60 and 65 degrees from normal. The optimal angle increases to around 70 degrees for a roughened substrate. Even at the optimal slant angle, the applied shearing stress as a ratio of the compression applied to the specimen decreases as the surface roughness increases, starting at 26 percent for a smooth substrate and decreasing to 18 percent for a rough substrate. Therefore, even for specimens prepared at the optimal angle, significantly greater levels of compression will be needed to produce bond failure in a roughened sample, increasing the likelihood that the sample will fail in compression prior to slip failure in shear.

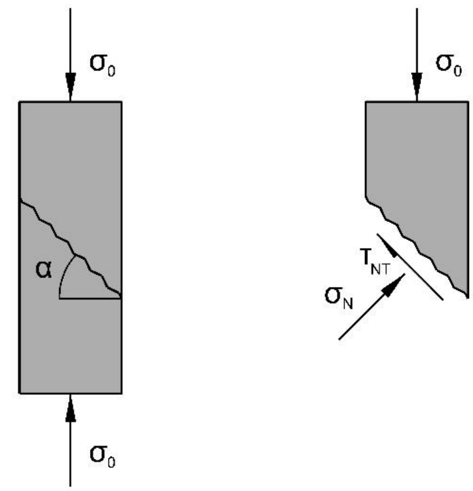


Figure E-1 – Diagram showing (1) the slant shear specimen under uniaxial compression stress and (2) the resulting stresses on the bond surface

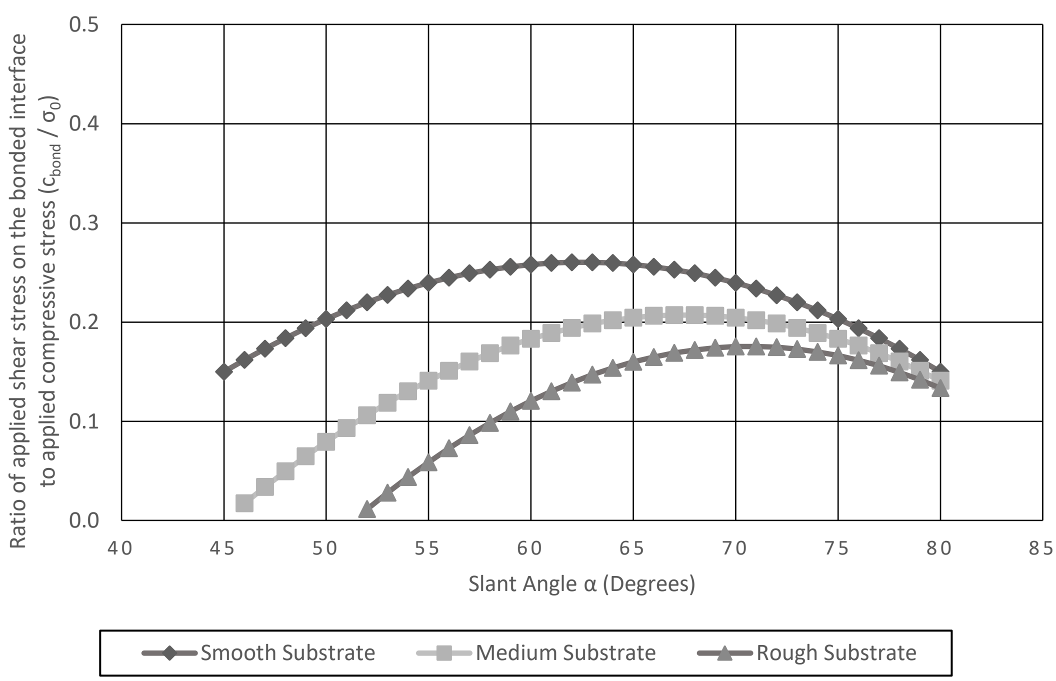


Figure E-2 – Applied shear stress at bonded interface (c_{bond}) as a ratio of applied compressive stress (σ_0), varying surface roughness, after Austin, et al. (1999)

E.2 Observed Effect of Surface Roughness on Failure Mode

The observed failure mode of all 24 slant shear specimens tested during the research program was one of compression failure. The desired failure mode for the test was failure in shear along the bonded interface, as this result would have been indicative of the shear strength of the bonded interface. However, it appears that the clamping force on the roughened bond plane was sufficient to resist the applied shear force on the 45 degree bond plane. For well-prepared bonded samples, some compressive-type failures are to be expected when testing slant shear cylinders (Kriegh, 1976). However, it was noted that even the weakest bonded surface (Slab 2B) failed in compression and not in shear failure at the bonded interface. Referencing the curves developed in Figure E-2, the shearing stress on the bonded interface at a 45 degree slant is equal to about 15 percent of the applied compressive stress for a relatively smooth substrate surface. For Slab 2B, the direct shear test produced an average shear strength of 1.19 MPa (173 psi). Applying the curve value of 15 percent, one would expect slip failure along the bond surface at a compressive stress of 1.19/0.15 = 7.93 MPa (1,150 psi). Instead, the observed failure of the Slab 2B slant shear specimen occurred at a compressive stress exceeding 35 MPa (5,000 psi). It appears that Concrete Surface Profile 6 used in the preparation of the substrate is sufficiently rough to dramatically increase the frictional slip resistance resulting from the normal (clamping) force when the slant angle is 45 degrees.

E.3 Transformed Slant Shear Results

Compression stresses on the slant shear cylinders at failure have been included in Chapter 4.7. From these tables, using the stress transformations discussed in Chapter 3.2.5, the maximum shear stress (at compression failure) at the bonded interface may be calculated, as shown in Tables E-1 (SI units) and E-2 (US customary units). A statistical analysis was performed on the dataset to compute the average shear strength, standard deviation, and coefficient of variation. The statistical analysis was omitted for Slabs 1B and 2B due to lack of data.

Table E-1 – Maximum Shear at Slant Interface (SI units)

Slab ID	Pretreatments	*Shear Stress at Interface (kPa)*				*Statistical Analysis*		
		Test 1	*Test 2*	*Test 3*	*Test 4*	*Average (kPa)*	*Std. Dev. (kPa)*	*COV*
1A	Dry / No Agent	18,706	12,831	16,610	18,430	16,644	2344	14.1%
1B	Dry / Wet Agent	20,671		20,284		20,478		
2A	SSD / Wet Agent	22,374	18,843	19,250	19,381	19,962	1406	7.0%
2B	SSD / Dried Agent	17,506				17,506		
3A	Wet / Wet Agent		14,989	13,796	18,195	15,660	1857	11.9%
3B	SSD / No Agent	19,533	15,458	18,223	13,321	16,634	2786	16.8%

Table E-2 – Maximum Shear at Slant Interface (U.S. customary units)

Slab ID	Pretreatments	*Shear Stress at Interface (psi)*				*Statistical Analysis*		
		Test 1	*Test 2*	*Test 3*	*Test 4*	*Average (psi)*	*Std. Dev. (psi)*	*COV*
1A	Dry / No Agent	2,713	1,861	2,409	2,673	2,414	340.0	14.1%
1B	Dry / Wet Agent	2,998		2,942		2,970		
2A	SSD / Wet Agent	3,245	2,733	2,792	2,811	2,895	204.0	7.0%
2B	SSD / Dried Agent	2,539				2,539		
3A	Wet / Wet Agent		2,174	2,001	2,639	2,271	269.4	11.9%
3B	SSD / No Agent	2,833	2,242	2,643	1,932	2,413	404.1	16.8%

E.4 Discussion of Slant Shear Results

Based on the observed failure mode, it was suspected that the strength results were affected primarily by the compressive strength of the concrete, and not by the properties of the bond. It was further surmised that both the substrate and overlay compressive strengths jointly controlled the failure mode. To test this premise, the shear strength result was divided by the average of the substrate and overlay compressive strengths. Table E-3 lists the adjusted results. Note that $\tau / f'_{c,avg}$ is unitless, therefore, the table has not been reproduced in SI units.

Table E-3 – Slant shear strength adjustment (U.S. customary units)

Slab ID	*Pretreatments*	*28 Day Compressive Strength (psi)*		*Avg. Interfacial Shear at Failure (τ) (psi)*	*Factored Interfacial Shear at Failure $\tau / f'c_{(avg)}$*
		Substrate	*Overlay*		
1A	Dry / No Agent	6,092	5,951	2,414	0.40
1B	Dry / Wet Agent	6,092	6,879	2,970	0.46
2A	SSD / Wet Agent	5,683	6,244	2,895	0.49
2B	SSD / Dried Agent	5,683	4,625	2,539	0.49
3A	Wet / Wet Agent	6,266	6,583	2,271	0.35
3B	SSD / No Agent	6,266	3,069	2,413	0.52

At a slant angle of 45 degrees, the transformed shear stress on the slant surface is equal to one-half of the applied compressive stress on the cylinder. Therefore, a failure in compression should result in a $\tau / f'_{c,avg}$ ratio of about 0.50. Indeed, this appears to be the case for the majority of specimens. Slabs 1A and 3A, with ratios of 0.40 and 0.35, respectively, did fail prior to the anticipated compressive strength of the concrete. However, even for these samples, the observed failure mode was not in shear at the bond surface. This analysis confirms that the results are representative only of the compressive strength of the concrete.

Figure E-3 graphs the results of the slant shear tests with the average compressive strength of the substrate and overlay slabs corresponding to each sample. A best fit line has been added to illustrate the relationship.

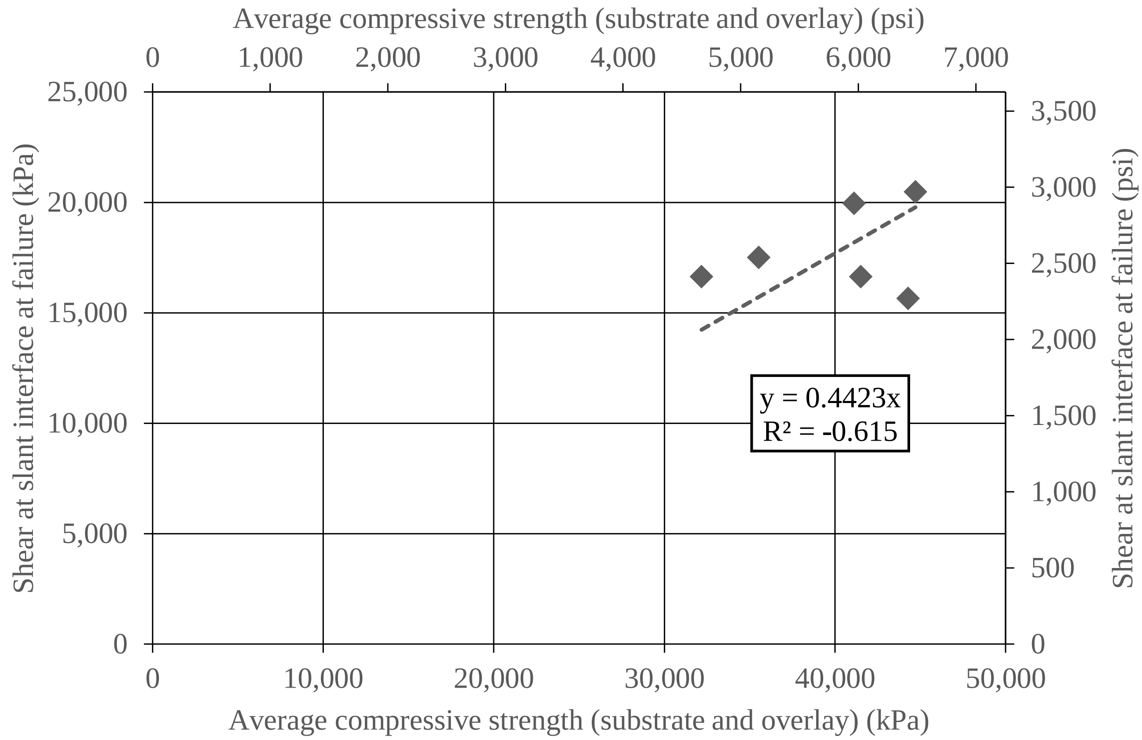


Figure E-3 – Compressive strength vs. measured slant shear strength

E.5 Conclusions

The observed failure mode and analysis of the results confirm that the results of the slant shear specimens are unaffected by the shear strength of the bonded interface and are indicative solely of the compressive strength of the concrete.

Although the majority of slant shear samples are prepared in the laboratory using a cylinderical mold and plate, some past research has had good success testing slant shear samples obtained via coring. However, obtaining these cores outside of a laboratory environment presents some unique challenges, since a coring angle of 60-degrees or greater is beyond the capability of the equipment used in this test and would have required a special jig and additional footprint on each overlay slab.

It is concluded that the slant shear test using cored specimens does not lead to a reliable measure of shear stress at a bonded concrete interface.