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VTRC 07-CR17

RECOMMENDATIONS FOR THE CONNECTION BETWEEN FULL-DEPTH PRECAST BRIDGE DECK PANEL SYSTEMS AND PRECAST I-BEAMS

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16. Abstract

Precast bridge deck panels can be used in place of a cast-in-place concrete deck to reduce bridge closure times for deck replacements or new bridge construction. The panels are prefabricated at a precasting plant providing optimal casting and curing conditions, which should result in highly durable decks. Precast panels can be either full-depth or partial-depth. Partial-depth panels act as a stay-in-place form for a cast-in-place concrete topping. This study investigated only the behavior of full-depth precast panels.

The research described in this report had two primary objectives. The first was to develop a performance specification for the grout that fills the haunch between the top of the beam and the bottom of the deck panel, as well as the horizontal shear connector pockets and the panel-to-panel joints. Tests were performed using standard or modified ASTM tests to determine basic material properties on eight types of grout. The grouts were also used in tests that approximated the conditions in a deck panel system. Based on these tests, requirements for shrinkage, compressive strength, and flow were established for the grouts. It was more difficult to establish a test method and an acceptable performance level for adhesion, an important property for the strength and durability of the deck panel system.

The second objective was to quantify the horizontal shear strength of the connection between the deck panel and the beam prestressed concrete beams. This portion of the research also investigated innovative methods of creating the connection. Push-off tests were conducted using several types of grout and a variety of connections. These tests were used to develop equations for the horizontal shear strength of the details. Two promising alternate connections, the hidden pocket detail and the shear stud detail, were tested for constructability and strength.

The final outcome of this study a set of recommendations for the design, detailing, and construction of the connection between full-depth precast deck panels and prestressed concrete I-beams. If designed and constructed properly, the deck panel system is an excellent option when rapid bridge deck construction or replacement is required.

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Full-depth precast bridge deck panels, grout performance specification, deck panel girder connection, horizontal shear strength

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ABSTRACT

Precast bridge deck panels can be used in place of a cast-in-place concrete deck to reduce bridge closure times for deck replacements or new bridge construction. The panels are prefabricated at a precasting plant providing optimal casting and curing conditions, which should result in highly durable decks. Precast panels can be either full-depth or partial-depth. Partial-depth panels act as a stay-in-place form for a cast-in-place concrete topping. This study investigated only the behavior of full-depth precast panels.

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The final outcome of this study a set of recommendations for the design, detailing, and construction of the connection between full-depth precast deck panels and prestressed concrete I-beams. If designed and constructed properly, the deck panel system is an excellent option when rapid bridge deck construction or replacement is required.

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INTRODUCTION

Precast bridge deck panels can be used in place of a cast-in-place concrete deck to reduce bridge closure times for deck replacements or new bridge construction. The panels are prefabricated at a precasting plant providing optimal casting and curing conditions. The panels can be transported to the bridge site for immediate erection. Precast panels can be either full-depth or partial-depth. Partial-depth panels act as a stay-in-place form for a cast-in-place concrete topping. This research program only investigates the behavior of full depth precast panels.

Figure 1 shows a representation of a bridge with precast deck panels and prestressed concrete beams. The construction process consists of first placing the panels on top of the beams. The self weight of the panels is transferred to the beams through leveling bolts. Leveling bolts are threaded through the depth of the panels and protrude through the bottom of the panels. The protrusion can be adjusted depending on the desired haunch height or desired top-of-deck elevation. For the purposes of this report, the haunch is defined as the grout or concrete between the top of the beam and the bottom of the deck. The transverse joints are filled next. If the deck is to be post-tensioned, this operation is then performed. After the post-tensioning operation is complete, the post-tensioning ducts are grouted. The haunch is placed after the post-tensioning operation. Once the grout in the haunch has cured, the leveling bolts are removed and the panels and beams act as a composite system. Barrier rails are then cast and a wearing surface may be placed.

The most common type of joint between adjacent panels is a grouted female-female shear key; an epoxied male-female shear key is also an option. Either type of joint creates a mechanical interlock that provides continuity between the panels. The panels are post-tensioned together to add strength to the joint, provide distribution reinforcement, reduce the chance for cracking and water leakage at the joint, and improve the durability of the deck. However, if post-tensioning is not applied, mild reinforcing steel should be placed across the joint in order to properly reinforce the joint. The mild reinforcing steel must be properly developed on each side of the joint.

Composite action between the deck and beams is provided by shear connectors that extend out of the beam and into the shear pockets of the panels. The connectors typically consist of either hooked reinforcing bars or shear studs. The beams can be either precast, prestressed concrete beams or steel girders. Precast, prestressed beams are used in this research program.

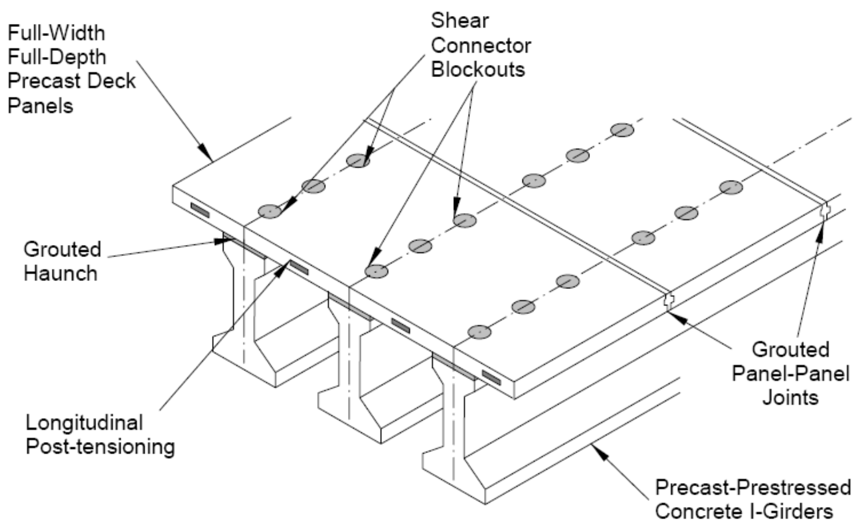


Figure 1. Representation of Bridge Deck Panel System

Grout for Haunches and Shear Pockets

There are many types of performance-based properties that distinguish one grout from another. The properties that are important to precast bridge deck panel systems can be organized into three basic categories: strength, durability and constructability. These properties are summarized in Table 1. For a precast deck panel project to proceed smoothly and for the system to be durable over the service life of the bridge, the properties of the grout must be properly specified. A performance based specification for the grout, which sets requirements for test results on the important properties, is necessary to ensure a maintenance free and long lasting precast bridge deck.

This research program investigated several of the important physical characteristics of the grout for the haunch and pocket. Results for several types of grout in ASTM standard or slightly modified tests were compared to results from tests representative of the conditions in a haunch and pocket. These results were then analyzed to develop a recommended grout specification.

Table 1. General Performance-Based Grout Properties

Strength	Durability	Constructability
Compressive	Shrinkage	Work Time
Tensile	Freeze/Thaw	Set Time
Bond	Sulfate Resistance	Flow
	Chloride Ingress	

Horizontal Shear Connectors

Composite action between the panels and beams is provided by the haunch and shear connectors which are clustered together at the shear pockets. This is quite different from the uniform shear connector spacing found with cast-in-place concrete decks. The discrete locations of the shear connectors raise questions about the proper way to design for horizontal shear. The pocket spacing is typically 2 ft. Larger pocket spacing is desirable because it results in less grout that has to be placed during the bridge closure and fewer pockets to be formed during panel fabrication. Larger pocket spacing may result in cracking along the interface between the shear pockets where there is no reinforcement present. Current design provisions do not address the design of shear connectors for precast bridge deck panel systems.

There are a variety of shear connectors that can be used with precast bridge deck panel systems. Hooked reinforcing bars are a simple option for panels installed on prestressed concrete beams. Shear studs are the most common type for panels installed on steel girders. This research program investigates the performance of shear studs and hooked reinforcing bars with precast, prestressed beams. The hooked reinforcing bars are cast into the beam. A portion of the hooked reinforcing bar protrudes from the top flange of the beam into the shear pocket. The shear connector detail with the shear studs is fabricated by casting a steel plate in the top flange of a prestressed beam. Shear studs are located on the bottom of the steel plate. This is shown in Figure 2. Additional shear studs can then be welded directly on to the top of the steel plate after the beam is erected and the panels have been placed. No prior use or testing of this detail was found in the literature review presented in Wallenfelsz (2006).

Post-installed hooked reinforcing bars have also been proposed in deck replacement projects. Shear connectors that are post-installed reduce the tripping hazard associated with shear connectors during early construction phases. They also ensure that all the shear connectors fit in the shear pockets when casting tolerances are exceeded.

PURPOSE AND SCOPE

The first objective of this project was to develop a performance specification for the grout that fills the haunch between the top of the beam and the bottom of the deck panel, as well as the horizontal shear connector pockets and the panel-to-panel joints. Tests were performed using standard or modified ASTM tests to determine basic material properties on eight types of grout. The grouts were also used in tests which approximated the conditions in a deck panel system.

Figure 2. New Detail For Horizontal Shear Reinforcement

Based on these tests, requirements for shrinkage, compressive strength and flow were established for the grouts. It was more difficult to establish a test method and acceptable performance level for adhesion, an important property for the strength and durability of the deck panel system.

The second objective was to quantify the horizontal shear strength of the deck panel to beam connection for prestressed concrete beams. This portion of the research also investigated more innovative methods of creating the connection. Push-off tests were conducted using several types of grout and a variety of connections. These tests were used to develop equations for the horizontal shear strength of the details. Two promising alternate connections, the hidden pocket detail and the shear stud detail, were tested for constructability and strength.

The results were used to recommend guidelines for the connection of precast deck panels to precast I-beams. Recommendations are made for (1) grout specifications, (2) design methods for horizontal shear transfer, and (3) types of shear connectors.

METHODS AND MATERIALS

Development of Grout Specification

General Grout Properties

Strength

In order to open a bridge utilizing a precast deck panel system to traffic as soon as possible, rapid grout strength gain is of utmost importance. Most grouts used for highway patching are rated for a compressive strength of 2500 psi in two hours. This is certainly an impressive statistic, but it is important to note that these grouts are usually used to fill shallow cracks and small areas of damaged concrete. In a precast deck panel system, the grout needs to fill an area as deep as the deck itself, between 7 in. and 10 in., as well as the haunch between the deck and beams, which can range from 1 to 3 in. For such a deep and voluminous pour, it is possible to use a small coarse aggregate (pea gravel) extension, which allows the grout to pour more like concrete and to extend the yield volume of the grout, reducing costs. Using the proper aggregate extension is vital to ensure that the reduction in initial compressive strength is not too great, and that the consistency of the grout does not become too thick, hindering its ability to flow through the confines of the haunch. The goal of using a grout in a precast deck panel system is to achieve a compressive and tensile strength similar to that of the deck concrete. This will ensure a fairly uniform structural consistency in the deck and more importantly, sufficient composite action between the deck and the beams.

Bond or adhesion between the grout and the concrete of the deck and beam is important to ensure sufficient horizontal shear strength of the deck panel system. Currently, ACI 318-02, the *AASHTO Standard Specifications for Highway Bridges* and the *AASHTO LRFD Bridge Design Specifications* provide design equations for horizontal shear strength between a precast beam and a cast-in-place deck, which involves one shear plane. However, it is not clear if these equations are applicable for horizontal shear strength between two precast members, which involves two shear planes, one between the grout and deck and one between the grout and beam. Menkulasi and Roberts-Wollmann (2002, 2003) have proposed equations for horizontal shear resistance in precast concrete deck panels on concrete beams based on their research.

Durability

Most grouts under consideration for use in precast deck panel systems are considered non-shrink. This does not mean that the grout does not shrink; rather, it shrinks a very small amount. Differential shrinkage between the grout and the precast concrete must be limited to ensure that cracks do not form along the interface, reducing the horizontal shear capacity of the system. Grout shrinkage can also lead to cracks at the shear pocket interface or at panel-to-panel joints. This could allow water and deicing agents to seep through the deck, which has been known to cause significant damage to the girders.

Freeze/thaw resistance measures a material's ability to withstand cold/warm cyclic temperature changes. Sulfate resistance and chloride ingress are properties that describe a material's durability when exposed to sulfates and chlorides such as deicing chemicals and other road debris. While these are all important characteristics for long-term durability, they were not investigated in this research.

Constructability

Since most candidate grouts boast high early strength gain, constructability can be a concern. Most grouts specify that mixing, placing and finishing must be completed within 10 to 15 minutes. To ensure a high quality horizontal shear connection, the grout must completely fill the shear pockets and distribute evenly through the haunches. If the workability of a grout is poor and the initial set time short, it is very possible that the ability of the grout to flow will be adversely affected. Achieving a balance between high early strength and flow capability is critical.

Grout Properties Investigated in This Research

The performance-based grout properties that have been identified as important to ensuring a horizontal shear connection of high initial quality are:

- Compressive Strength
- Tensile Strength
- Shrinkage
- Flow
- Workability
- Bond Strength

Eight candidate grouts were evaluated with respect to these properties and the results were used to determine optimal performance criteria for a precast bridge deck panel system.

Candidate Grouts and Corresponding Concrete

Four candidate grouts were analyzed through a series of tests in order to investigate the properties listed above. They were evaluated as neat grouts (no aggregate extension) and as extended grouts, using a 3/8 in. pea gravel aggregate extension, for a total of eight grouts. A companion concrete batch was prepared for each grout. The concrete was needed as a base material for many of the experiments as it represented the concrete beam and concrete deck panel. Mixing information for each grout and concrete is provided in Tables 2 and 3.

A list of pre-qualified concrete repair grouts was obtained from VDOT and four were selected for investigation in this research. ThoRoc® 10-60 Rapid Mortar is a Degussa Building Systems product. It was previously marketed by Fosroc as Patchroc® 10-60 Rapid Mortar. SikaQuick® 2500 is a relatively new material that was introduced in 2003 by Sika Corporation of Lyndhurst, New Jersey, and has become popular among DOTs. Five Star® Highway Patch is distributed by Five Star Products, Inc. of Fairfield, Connecticut. Set® 45 is distributed by Master Builders, Inc. of Cleveland, Ohio, a Degussa Company. Set® 45 Hot Weather was selected because it allows for longer working time in elevated temperature conditions. All of these products are identified as rapid hardening, high early strength gain repair mortars. ThoRoc® 10-60, SikaQuick® 2500 and Five Star® Patch are all cement-based, while Set® 45 Hot Weather is magnesium-phosphate based. Water and aggregate extension amounts used in this research were based on manufacturer recommendations and vary for each product.

For each series of grout tests, a corresponding batch of concrete was prepared at least 28 days in advance. This concrete is a nominal 4000 psi mix design. Component quantities by weight are provided in Table 3. Cylinders were made to determine compressive and tensile strength of the concrete at the time of the grout tests. Compressive strength was obtained in accordance to ASTM C 39 (2002): Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. Tensile Strength was obtained in accordance to ASTM C 496 (1996): Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens.

Description of ASTM Tests and Representative Tests

Compressive Strength

The compressive strength for each grout was obtained in accordance with ASTM C109 (2002): Standard Test Method for Compressive Strength of Hydraulic Cement Mortars Using 2-in. Cube Specimens (modified). Since an important characteristic of a grout is early strength gain, compressive strengths were obtained at one hour, two hours, one day and seven days, rather than the standard 28 days. Three cubes were tested at each time interval, and the reported strength is the average of the three cubes.

Table 2. Candidate Grouts and Mixing Information

ID No. and Product Name		Mixing Quantities per 50-lb, Bag					
		Initial Water, pints	**Additional Water, pints**	**Aggregate Extension, % by weight**	**Aggregate Extension, lb**	**Yield Volume, cu. ft.**	**Cost per bag, $**
Neat Grout	**1.** ThoRoc® 10-60 Rapid Mortar	5.50	1.00	0	0	0.43	12.75
	2. SikaQuick® 2500	5.00	0.50	0	0	0.43	13.75
	3. Five Star® Highway Patch	5.00	1.00	0	0	0.40	20.50
	4. Set® 45 Hot Weather	3.25	0.50	0	0	0.39	24.00
Extended Grout	**5.** ThoRoc® 10-60 Rapid Mortar	5.50	1.00	50	25	0.57	12.75
	6. SikaQuick® 2500	5.00	0.50	50	25	0.60	13.75
	7. Five Star® Highway Patch	5.00	1.00	80	40	0.66	20.50
	8. Set® 45 Hot Weather	3.25	0.50	60	30	0.58	24.00

Table 3. Concrete Mix Quantities

Component	Quantity/batch	Quantity/CY
Type I/II Portland Cement	46.0 lb	637 lb
Coarse Aggregate (angular)	125.1 lb	1732 lb
Fine Aggregate	92.7 lb	1284 lb
Water	21.6 lb	299 lb
Air Entrainer	10.2 ml	141 ml
Retarder	13.0 ml	180 ml
Yield Volume	**1.95 cu. ft.**	**27 cu. ft.**

Tensile Strength

The tensile strength for each grout was obtained in accordance with ASTM C 496 (1996): Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens. In this test method, a cylinder is placed on its side and a compressive load is applied along a diameter. A splitting tensile strength can then be calculated based on the cylinder's dimensions and the maximum applied load. In this research, 4 in. by 8 in. cylinders were used to obtain splitting tensile strengths at one day and seven days. Two cylinders were tested at each time interval, and the reported strength is the average of the two cylinders.

Shrinkage - ASTM C 157

Shrinkage for each grout was regularly obtained over a 28 day period in accordance with ASTM C 157 (1999): Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete (modified). Readings were then taken less frequently for over one year. Grout was placed in rectangular prism bar molds 11 in. long with nickel alloy studs inserted at each end. Neat grouts, or grouts without an aggregate extension, were tested using 1 in. square cross section bars. Grouts with an aggregate extension were tested using 3 in. square cross section bars. A length comparator measured the outside distance between studs in order to determine shrinkage over time.

Shrinkage bars were allowed to cure in laboratory ambient air conditions. This allowed them to experience slight temperature and humidity changes as would be the case for grouts used in a bridge deck panel system. Since the coefficient of thermal expansion for each grout is low (6-7 $\mu\varepsilon/^{o}F$), and the laboratory temperature did not vary greatly ($\pm 5^{o}F$ within the first 28 days) , temperature effects did not greatly alter the shrinkage values (±30με out of 300-800με). Four shrinkage bars were prepared for each neat grout and three shrinkage bars were prepared for each aggregate extended grout. Three shrinkage bars were also prepared for each corresponding concrete batch. ASTM C 596 (2001) is a similar specification which can also be used to determine shrinkage of grouts.

Representative Test: Shear Pocket with Ponding

A critical location of a precast deck panel system in which grout shrinkage could affect the beam-panel connection is the shear pocket. Relative shrinkage differences between the concrete and the grout could cause tensile stresses along the interface, which could result in cracking and leaking of water through the panel. Minimizing leaking is especially important in areas of cold weather climate so that deicing agents do not seep through the deck and cause deterioration of the bridge girders.

To model relative shrinkage of concrete and grout in a shear pocket, a 12 in. by 12 in. by 4 in. deep block of concrete was cast with a centered 6 in. diameter circular cutout. After the concrete had cured for at least 28 days, grout was poured into the 6 in. pocket. Then after the grout cured, a thin layer of water was ponded over the entire 12 in. by 12 in. area. This test is illustrated in Figure 3 and Figure 4. Careful observations were made regarding cracks between the grouts and concrete and water leaking through the interface. Two specimens were created for each candidate grout.

Flow and Workability- ASTM C 1437 and ASTM C 230

Each candidate grout was mixed according to manufacturer recommendations. First an initial amount of water is placed in the mixer, then the grout powder is added while the mixer turns. When approximately 80% of the powder is added, an additional specified amount of water is supplied to the mix, which significantly improves its workability. For batches with a pea gravel aggregate extension, all of the aggregate for each batch is placed in the mixing container with the initial water before any powder is added. Since the required yield volume for these experiments was small compared to what would be needed for an actual precast panel system, standard 50 lb bags of grout were used along with a medium-speed drill and paddle mixer

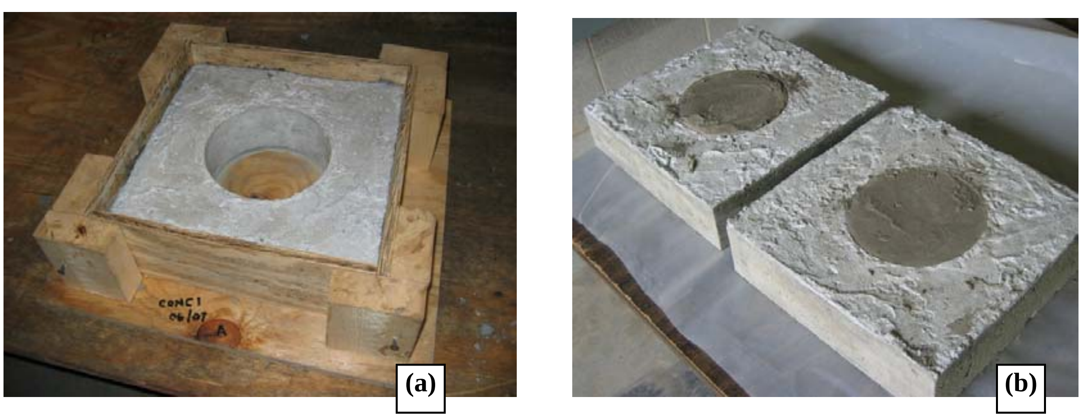


Figure 3. Shear Pocket Specimen Before (a) and After (b) Filling with Grout

Figure 4. Shear Pocket Specimen with Water Ponding

. Flow characteristics for each grout were measured in accordance with ASTM C 1437 (2001): Standard Test Method for Flow of Hydraulic Cement Mortar (modified). Specifications for the flow table and truncated flow cone are found in ASTM C 230 (1998): Standard Specification for Flow Table for Use in Tests of Hydraulic Cement. The test setup is shown in Figure 5.

Figure 5. Truncated Flow Cone and Drop Table

Immediately after the grout was mixed, the proper amount was placed in the flow cone. After the cone was completely filled and the table was wiped clean of any excess grout, the cone was lifted vertically to allow the mortar to slump under its own self weight. The horizontal spread was measured at its widest and narrowest dimension. This information was used to calculate the average percent increase of the grout's original diameter of 4 in. This allows for quantification of the grout's ability to flow under its own power, without the help of vibration or any external force. Once these measurements were obtained, the table was dropped 10 times within 15 seconds. This is a modification to the standard test method which calls for 25 drops within 15 seconds. The reason for this modification is because these particular types of grouts tend to flow better than the average mortars for which this test method is intended. Twenty-five drops would result in the grout spreading across the entire 10 in. diameter of the table and the purpose of the test would be lost. It is important to measure how each grout flows when forced by vibration or some other method. Once again, the horizontal spread was measured at its widest and narrowest dimension in order to calculate an average percent increase of the grout's original diameter.

Representative Test: Haunch Flow Mockup

The following setup was designed to model a deck panel's shear pockets and haunch through which the grout must flow. A 4 in. thick rectangular concrete block was formed in plywood formwork that was 5 in. high. The concrete was given a trowel smooth finish. The block measured 1 ft wide by 2 ft long (see Figure 6a). A plywood cover was fixed over the base formwork with one "shear pocket" at each end of the block (see Figure 6b). The 2 ft spacing represents a typical spacing for shear pockets in a precast deck panel system, while the 8 in. pocket height represents a typical deck thickness. The 1 in. difference between the top of the concrete block and the bottom of the plywood cover represents a minimum haunch height between beam and panel through which the grout would have to flow. It is normal to encounter this tight haunch space near the mid-span of a precast, prestressed beam due to camber.

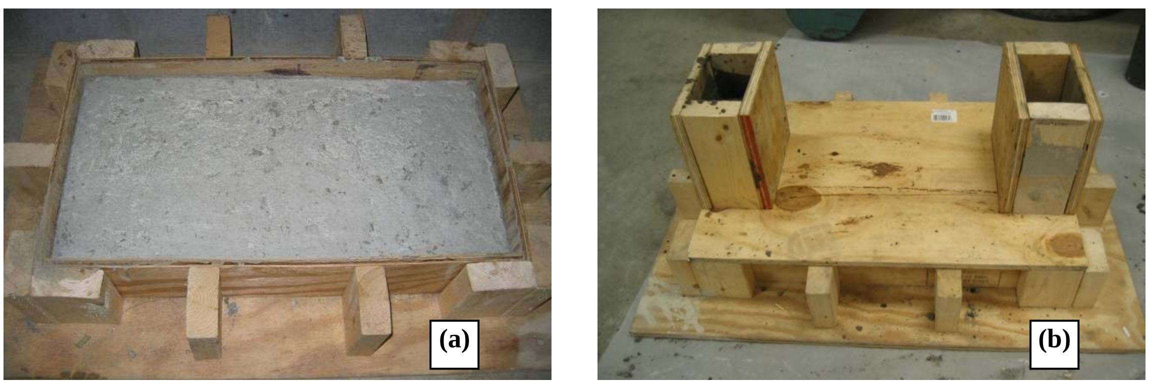


Figure 6. Haunch Flow Mockup Before (a) and After (b) Placement of Cover

After the grout was tested in the truncated flow cone, it was immediately poured down the left shear pocket and allowed to flow across the haunch. The objective of this experiment was to see how well each grout flows through a tight haunch spacing of 1in., forced only by the hydraulic head pressure provided by the height of the shear pocket. The grout must be able to completely fill the haunch space and then flow up the adjacent shear pocket. After one day, the plywood cover and shear pockets were removed. Qualitative observations were made based on the ability of the grout to completely fill the haunch and rise into the adjacent shear pocket. A good flow and a poor flow are illustrated in Figure 7.

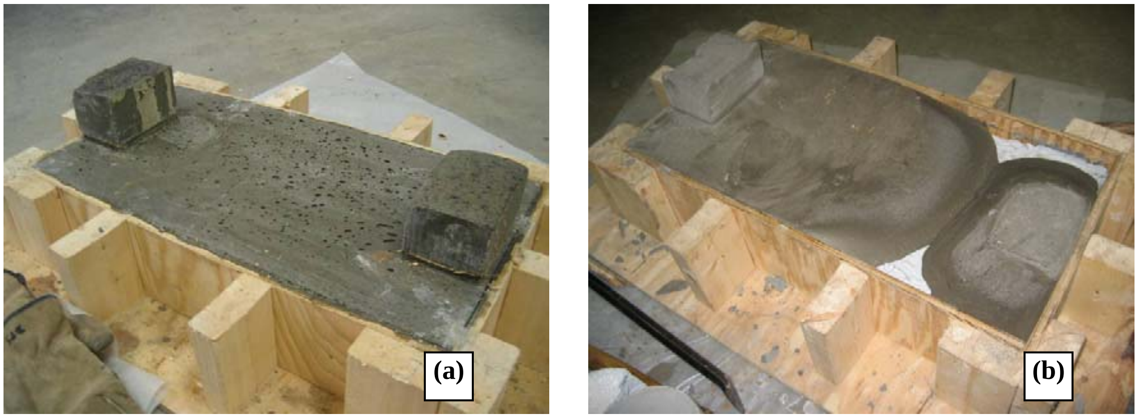


Figure 7. Good (a) and Poor (b) Grout Flow Through Haunch Mockup

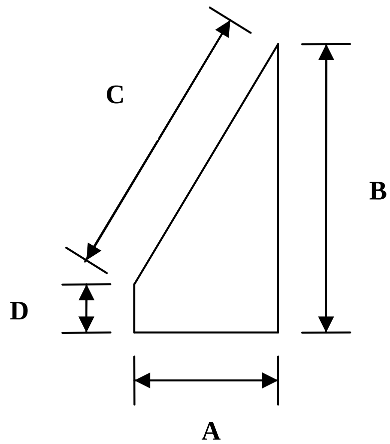
Bond Strength - ASTM C 882

The bond strength of each grout was investigated in accordance with ASTM C 882 (1999): Standard Test Method for Bond Strength of Epoxy-Resin Systems Used with Concrete by Slant Shear (modified). This test method calls for two halves of a 3 in. by 6 in. cylinder to be created by slicing the cylinder at 30^{o} from the vertical. The two half cylinders are then bonded together using an epoxy resin. The completed cylinder system is tested in compression to determine the bond strength of the epoxy resin.

For the purpose of this research, 4 in. by 8 in. cylinders were used. The lower portion of the cylinder was made of concrete. The grout was poured over top of the concrete base to complete the cylinder. The full cylinder was then tested in compression to determine the bond strength of the grout to the concrete. Figure 8 presents the dimensions of the half cylinders used in the ASTM standard and the dimensions used in this research.

In order to create concrete specimens in this fashion, plastic cylinder molds were filled with Plaster of Paris to supply rigidity. After one day, the cylinders were sliced in the specified orientation and the plaster was removed. The sliced cylinders were then placed in formwork to support the cylinder during the concrete placement (see Figure 9).

The slanted dimension of the cylinder form rested in a horizontal position in order to prepare the surface of the concrete in four different manners: a) smooth, b) exposed aggregate, c) raked, and d) raked and sandblasted. Three cylinders for each type of surface condition were formed in order to investigate optimal surface preparations for the precast beams and precast deck panels. A trowel was used to obtain the smooth surface. The exposed aggregate surface was obtained by spraying the fresh concrete with a surface retarder, which slows down the set time of the cement paste. After two hours, the top layer of cement paste was removed with a steel brush, exposing the concrete aggregates. A screw was used to obtain the raked surface, grooving an amplitude of ¼ in. Some of the raked specimens were sandblasted within a 24 hour period prior to pouring the grout. All four surface preparations for the concrete slant cylinder halves are shown in Figure 10.



Dimension	3 in. x 6 in. Cylinder	4 in. x 8 in. Cylinder
A: Diameter	3.000 in.	4.000 in.
B: Height	5.598 in.	7.464 in.
C: Slant Height	6.000 in.	8.000 in.
D: Base Height	0.400 in.	0.536 in.

Figure 8. Slant Cylinder Schematic and Dimensions

Figure 9. Sliced 4 in. x 8 in. Cylinders for Slant Cylinder Tests

A total of 12 concrete half cylinders were prepared for each grout. After they cured for at least 28 days, they were inserted into a whole 4 in. by 8 in. cylinder mold. Then the grout was poured into the mold to complete the cylinder (see Figure 11). Cylinders were tested in compression in order to investigate the early bond strength of each grout. Neat grout cylinders were tested one day after casting and aggregate extended grouts were tested two days after casting. Observations were made regarding whether the cylinder failed along the shear plane or if failure was due to significant cracking in the grout or concrete.

Representative Test: Push-Off Test

A push-off test was used to investigate the ability of a grout to resist horizontal shear loads in the haunch between a precast beam and precast deck panel. These tests have been used extensively in the past to investigate shear capacity between new concrete cast over precast concrete and were used recently by Menkulasi (2002) to investigate two precast elements with a grouted interface. The push-off tests described in this section were used for evaluating the bond of the grout to the concrete using specimens with no reinforcing. They were also used to investigate horizontal shear strength with reinforcement and to evaluate new types of horizontal shear connector details described later in this report.

For each test, two L-shaped concrete blocks were formed, one representing the beam (the beam side specimen) and one representing the deck panel slab (the slab side specimen). The specimens were then oriented as shown in Figure 12 and the shear pocket and haunch were filled with the grout. The specimen was then loaded directly along the center line of the haunch to failure. A small normal force was also provided to simulate the clamping stress that is supplied by the tributary weight of a deck panel per beam spacing as well as other dead loads.

For the first series of tests, investigating bond, the best surface preparations were determined for the beam side and slab side specimens and the three best-performing candidate grouts were selected to be used in the push-off tests based on the slant cylinder tests and other representative tests.

Specimen Details

The beam side specimen's dimensions and reinforcing details are provided in Figure 13. The concrete was placed with the specimen in the orientation shown. This simulates the placement orientation for a precast concrete beam, where the top of the beam is exposed to the air. For the bond evaluation tests, no shear connectors were used in order to solely investigate the horizontal shear strength provided by the grout. For other tests, several shear connector details were investigated.

The slab side specimen's dimensions and reinforcing details are provided in Figure 14. The specimen was poured in the shown orientation to simulate a deck panel pour, where the bottom of the slab rests against formwork. A 6 in. diameter cylinder mold was used to form the shear pocket.

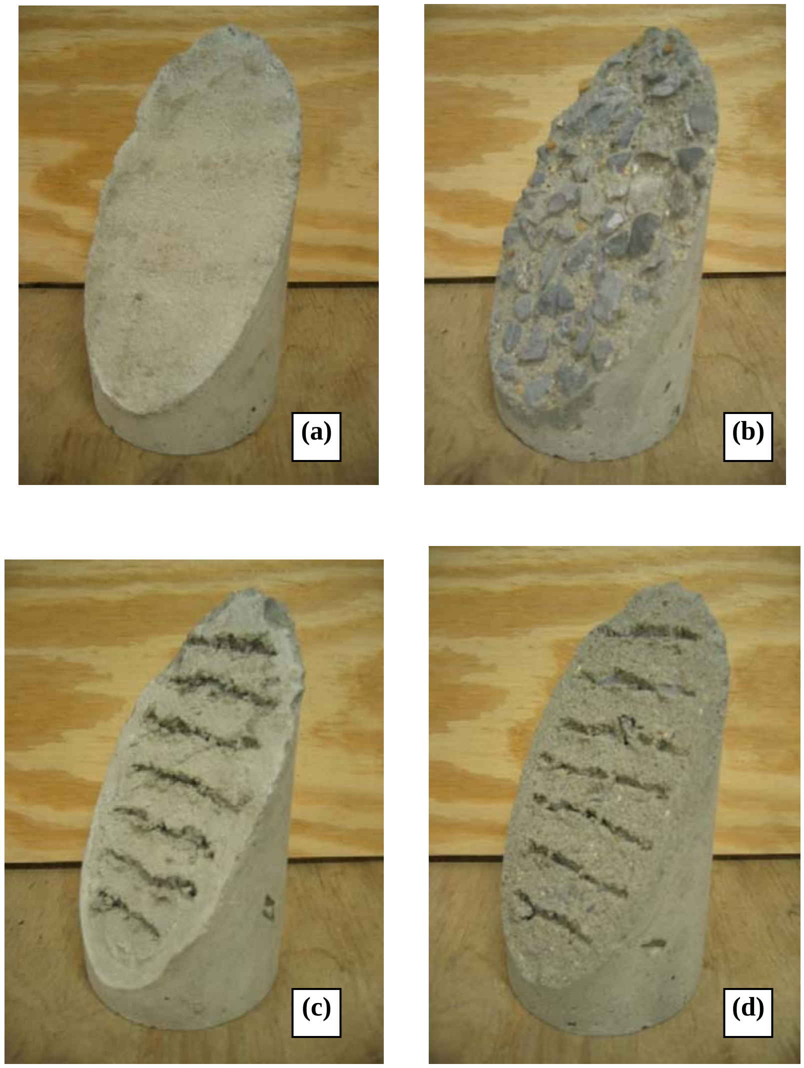


Figure 10. Slant Cylinder Concrete Surface Preparations:
Smooth (a), Exposed Aggregate (b), Raked (c), and Raked and Sand Blasted (d)

Figure 11. Completed Slant Shear Cylinder

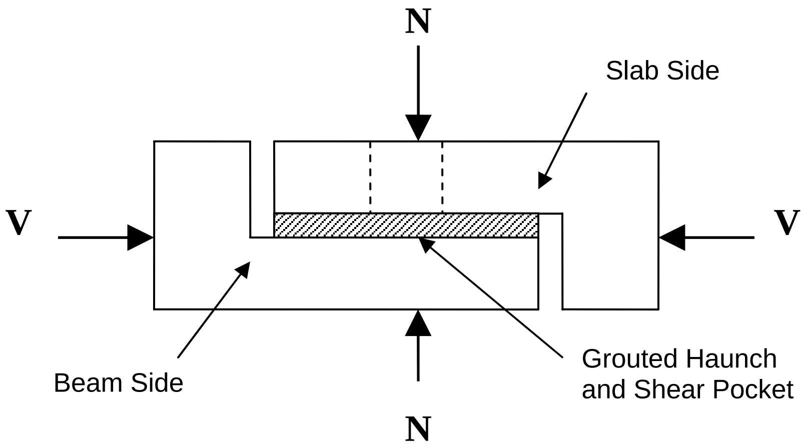


Figure 12. Typical Push-Off Test Setup

Based on the results of the series of grout tests, optimal surface conditions were determined for the push-off specimens. A raked surface was selected for the beam side, with a rake amplitude of ¼ in. (see Figure 15a). This is the conventional surface preparation for precast concrete bridge beams, although it may not be feasible if self-consolidating concrete is used. An exposed aggregate finish was selected for the bottom of the slab side (see Figure 15b). This surface preparation has been recommended previously for the underside of precast deck panels along beam lines. In order to achieve this surface condition, a coating of retarder was painted on the bottom of the formwork. One day after the concrete was poured, the slab specimens were removed from their forms. The bottom of the specimens were hosed and brushed to remove the cement paste layer and expose the aggregate.

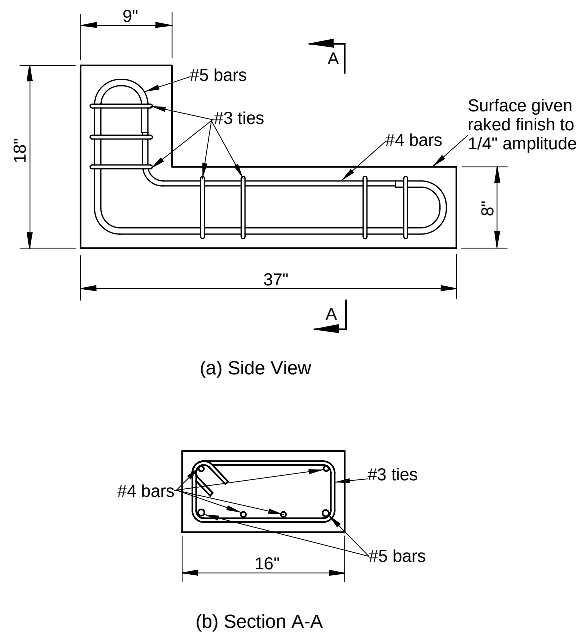


Figure 13. Beam Side Specimen Details

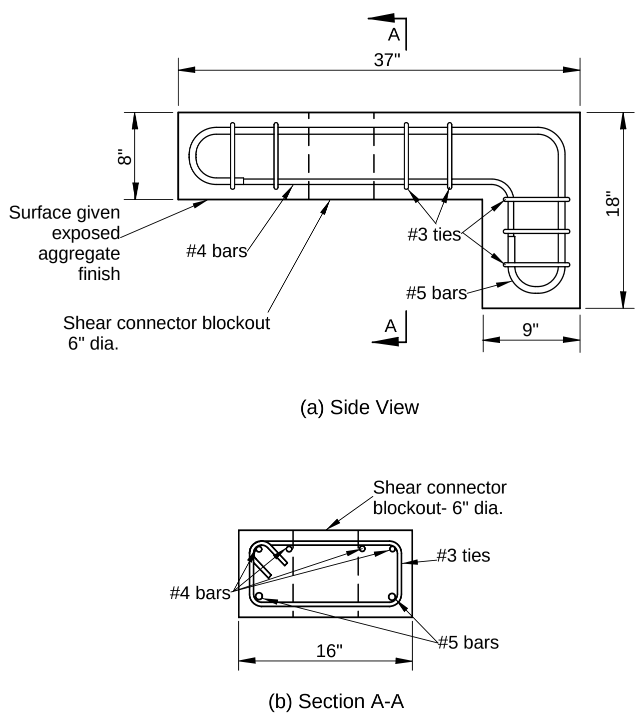


Figure 14. Slab Side Specimen Details

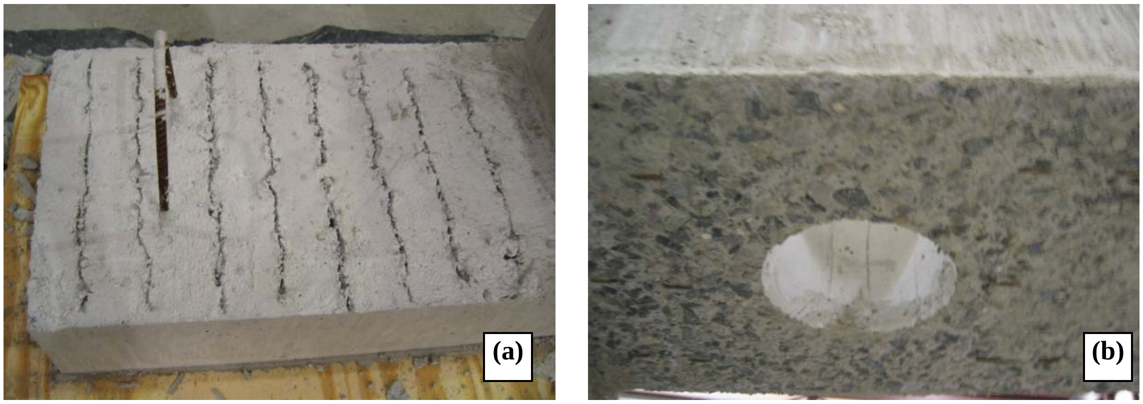


Figure 15. Beam Side (a) and Slab Side (b) Push-Off Specimen Surface Preparation

One difference between these push-off tests and the push-off tests performed by Menkulasi is the orientation of the specimen during the placement of the grout. The previous tests were grouted with the beam and slab elements resting on their side. The grout was poured through the side of the interface, not through the shear pocket. It was decided to arrange the new push-off tests in an upright position to better simulate the actual condition of a precast deck panel resting above the precast beam. A 1.5 in. haunch space was used; the specimens were also placed 1.5 in. apart horizontally in order to allow for sufficient relative displacement of the slab side and beam side during testing. Formwork was placed around the interface and the grout was poured through the shear pocket. The completed push-off specimen was tested two days later (see Figure 16).

Figure 16. Complete Push-Off Specimen with Grouted Interface

Test Setup

The push-off test setup consisted of two hydraulic rams, a roller-plate system, two end buttresses, two load cells to monitor loads and two potentiometers to monitor displacements. The setup is shown in Figure 17.

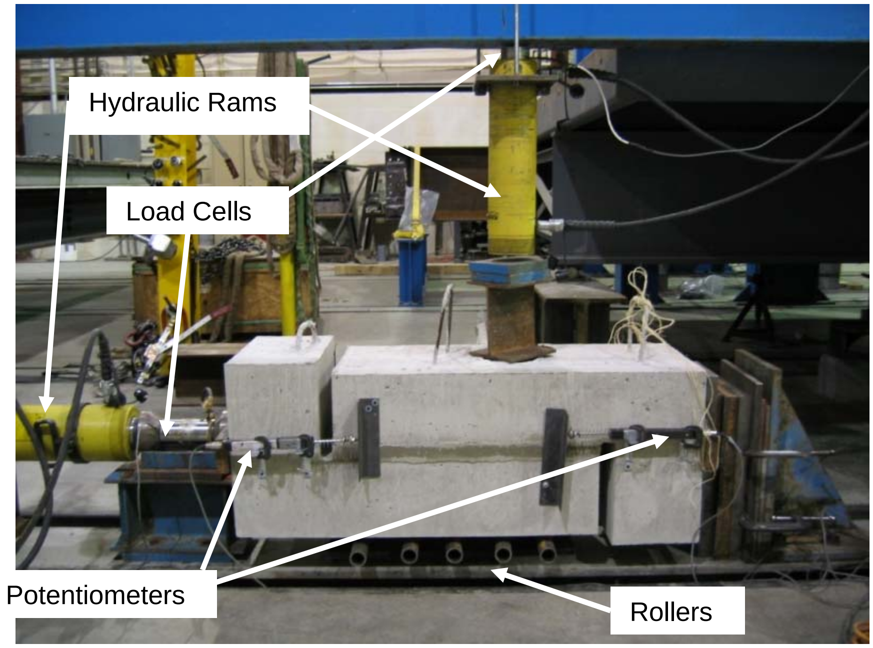


Figure 17. Push-Off Test Setup

The vertical ram was used to provide a normal force across the bonded interface. The horizontal ram applied force to a rectangular plate. That plate pushed against the beam side specimen and was centered with the haunch. The beam side rested on a roller-plate system that allowed it to displace relative to the slab side. The slab side was fixed in place by an end buttress and an identical rectangular plate that was also centered with the haunch. Two potentiometers monitored the relative displacements of the slab and beam specimens, with one affixed to each specimen. Since there was no shear reinforcement, it was expected that once the initial adhesion failed, the interface would experience a large slip and would not be able to sustain load.

Test Procedure

The vertical hydraulic ram was used to apply an initial load of 2500 lb, which is approximately the tributary weight of an 8.5 in. deck panel with a 2 ft pocket spacing on beams spaced at 10 ft. As the horizontal load increased, the concrete and grout interface expanded vertically due to Poisson's effect. This caused the normal force in the vertical ram to increase. Once the vertical load reached 4000 lb, it was reduced to the original 2500 lb loading. The horizontal shear loading was increased steadily over an approximately ten minute period until the bonded interface failed. The displacement was then increased until the horizontal space between the specimens closed. Observations were made regarding whether the interface failed between the grout and beam specimen or between the grout and slab specimen.

Summary of Tests to Develop Grout Specification

Table 4 summarizes the types and number of ASTM tests and representative tests used in this research to evaluate the properties of each candidate grout. Table 5 summarizes the types and number of ASTM tests used to evaluate the properties of each corresponding concrete.

Table 4. Test Summary for Each Candidate Grout

Test	No.
Compressive Strength	
ASTM C 109: 2 in. Cubes	
1 hour	3
2 hours	3
1 day	3
7 days	3
Tensile Strength	
ASTM C 496: Split Cylinders	
1 day	2
7 days	2
Shrinkage	
ASTM C 157: Shrinkage Bars	
Neat mortars (1 in.)	4
Extended mortars (3 in.)	3
Shear Pocket Ponding	2
Flow	
ASTM C 1437: Flow Cone	1
Haunch Mockup	1
Bond Strength	
ASTM C 882: Slant Shear Cylinder	
Smooth	3
Exposed Aggregate	3
Raked	3
Raked and Sand Blasted	3
Push-Off Test	
Mortar A	2
Mortar B	2
Mortar C	2

Table 5. Test Summary for Each Corresponding Concrete

Test	No.
Compressive Strength	
ASTM C 39: 4 in. x 8 in. Cylinders	2
Tensile Strength	
ASTM C 496: Split Cylinders	2
Shrinkage	
ASTM C 157: Shrinkage Bars (3 in.)	3

Further Grout Study: Pull-Off Tests

Following the initial series of grout tests presented in Table 4, further tests were performed to attempt to quantify adhesion of grouts to previously cast concrete. The test involved the casting of a concrete slab onto which 2-in. diameter grout discs were poured and then pulled off. The results indicate the amount of force required for the grouts to be pulled off the concrete and thus allow quantification of the adhesion between these two materials. Three samples of each of the eight grouts were tested for a total of 24 grout discs per test. The test was run three times, the first using a smooth dry concrete surface, and the second using a smooth saturated surface dry (SSD) concrete surface, and the third using a sand-blasted saturated surface dry smooth surface. A SSD surface is recommended by the instructions listed on the bags of grout.

Preparation of Materials and Procedure of Test

The materials needed for the tests were the following: molds for grout discs, a plywood form for the concrete slab, a small concrete slab, steel caps for each grout disc, and a mechanical testing device. The molds for the grout discs were made of 2-in. diameter PVC pipe. The pipe was cut into 1-in. lengths, sliced into two semi-circles, and then re-assembled with duct tape. They were sliced in order to easily remove them from the grout discs after the grout had set. A plywood form was constructed to cast the concrete slab on which the tests were performed. For simplicity, and to generally represent precast concrete, Quickcrete was used for the slab and welded wire reinforcement was placed to prevent cracking when the slab was flipped to result in its smooth side facing up (see Figure 18).

Figure 18. Plywood form created with reinforcing steel, and concrete slab poured

Once the Quickcrete had cured, cylinders were tested. After seven days, the Quickcrete cylinders were found to have compressive strengths of 2,430 psi and 2,550 psi, and the slab was determined to be adequate for the pull-off tests. Once the slab was ready, the PVC molds were sealed to it, using Silicon caulk, to keep them in place when the grouts were being placed (see Figure 19).

Eight different grouts were mixed, four neat and four extended, and placed into the molds. After the grouts had set, steel pipe caps were glued to each grout disc using PC-11® Marine Power White Epoxy Paste (see Figure 20).

Figure 19. PVC Molds for a Grout Disc to be Used in Pull-off Tests Glued to Concrete Slab

Figure 20. Steel Caps Glued to Grout Discs with PC-11® White Epoxy Paste

A hook was screwed into the steel caps. The hook was then attached to the mechanical testing device, as can be seen in Figure 21. After this, each specimen was pulled up slowly and the maximum loading, as shown on the dial, was recorded.

Figures 21. Testing Device for Pull-off Tests

Investigations of Horizontal Shear Strength

To examine the horizontal shear strength of a precast full-depth bridge deck panel system on precast beams, 29 push-off tests were conducted. This section describes the details and procedures used to fabricate, instrument and test each specimen. Haunch height was not one of the parameters investigated. Menkulasi (2002) found that varying the haunch height does not result in significant changes in the peak shear stresses obtained. Listed below are the various properties examined in this research.

- Shear connector type
- Cross-sectional area of shear connector
- Grout Type
- Surface Treatment
- Pocket Type

Material Properties

Concrete and Grout Material Properties

The compressive strength of the grout and concrete was measured each day of testing. The grout strength was measured in accordance with ASTM C109 (2002): Standard Test Method for Compressive Strength of Hydraulic Cement Mortars Using 2-in. Cube Specimens (modified). The compressive strength of the concrete was measured using 4 in. by 8 in. cylindrical specimens in accordance with ASTM C39 (2001): Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.

The concrete used to form the beam and slab side specimens for the 29 push-off tests which investigated horizontal shear strength was VDOT class A4 modified concrete. This type of concrete mix design is a standard Virginia bridge deck mix. The concrete was supplied by

CONROCK ready mix of Blacksburg, Virginia. The mix design for the concrete is presented in Table 6. This mix results in a slump of 2-4 in. and an air content of 6% (-½% to + 1½ %). The grouts used in this research were Five Star® Highway Patch and Set® 45 Hot Weather.

Table 6. Concrete Mix Design per yd^3

Material	Quantity	Source Location
Type I/II Cement	501 lb	Titan (Roanoke) Troutville, VA
Pozzolans	167 lb	Boral-Belews Creek Walnut Cove, NC
Sand	1203 lb	ACCO Blacksburg, VA
No. 57 Stone	1773 lb	ACCO Blacksburg, VA
Water	291 lb	Town of Blacksburg Blacksburg, VA
Admixture	varies	Sika Corporation Trenton, NJ
Retarder	varies	Sika Corporation Trenton, NJ
Water reducer	varies	Sika Corporation Trenton, NJ

Reinforcing Steel and Headed Shear Studs

Six tensile tests were performed on samples of the reinforcing bars to determine the actual yield stress of the material used. The reinforcing bars used were made of Grade 60 steel. Tensile test results can be found in Wallenfelsz (2006). No tensile tests were performed on the headed stud shear connectors and the yield stress of the connectors specified by the manufacturer of 49 ksi was used for all calculations. The Young's Modulus for both materials was 29,000 ksi.

Details of Push-Off Tests

Push-off tests were used to investigate the horizontal shear resistance of a precast concrete deck panel system on precast concrete beams. These tests were performed exactly as the previously described push-off tests investigating bond. The only difference was the presence of reinforcement across the joint.

Headed Stud Shear Connectors

A new detail was developed that has potential to ease construction difficulties. This detail entailed the use of headed studs with a precast beam. A problem that can arise during construction is that when precast beams and precast slabs are used the pockets and stirrups are in a fixed position. If there are any alignment problems and the two do not line up properly, major problems can result during erection.

The benefit of the welded stud system is that the slabs can be placed on top of the beams, they can be aligned and leveled. Then the studs can be welded onto the beam through the pockets. This not only eliminates problems associated with fabrication errors and misalignments, but the slabs are also much easier to place without having to guide the pockets over the studs.

In order to use welded studs on precast concrete beams, a steel plate must be attached to the surface of the concrete. This can be seen in Figure 22. Headed studs were welded to the bottom of a ¼ in. plate which was embedded into the concrete as the concrete was cast. The ¾ in.

headed studs to be used as shear connectors were then welded to the top of the beam specimen. The AISC Specifications for Structural Steel Buildings (1999) states that the stud diameter shall not exceed 2.5 times the flange thickness. For the test specimen, the plate thickness requirement was slightly violated (0.3 in. required and 0.25 in. provided). To ensure failure occurred in the haunch and pocket, the studs on the bottom of the plate embedded in the precast concrete outnumbered the studs used as shear connectors.

Hidden Pocket Detail

One problem with the precast bridge deck panel system is that the pockets, which extend through the deck to the riding surface, can be unattractive. One solution to this problem is the hidden pocket detail, which provides a more uniform and aesthetically pleasing bridge deck. Another option is to provide an overlay to the bridge deck.

Figure 22. Headed Shear Stud Specimen

The trial detail in this investigation was an inverted cone type detail as shown in Figure 23. Since the top of the pocket was 2 in. below the riding surface the only access to the pocket by grout is through the haunch. Once the haunch was formed, grout was pumped through the side port of the haunch. An important requirement of this detail is that grout vents be placed in the top of the pocket so that any air may escape. These grout vents exit at the top of the bridge deck and are small enough in diameter to not disturb the aesthetics of the bridge deck.

Instrumentation

The tests specimens were instrumented during testing exactly as described for the bond push off tests, except that electrical resistance strain gages were placed on the shear connectors before grouting. One gage was placed on the front side of one leg of the connector the other was placed on the other side of the opposite connector. The strain gages were placed such that they were at the mid-height of the haunch. The placement of the strain gages can be seen in Figure 24. The strain gage lead wires then exited the haunch either through the beam side specimen or through the bottom of the haunch. Due to the location and sensitivity of the strain gages some were damaged during grouting and others were damaged early in the test.

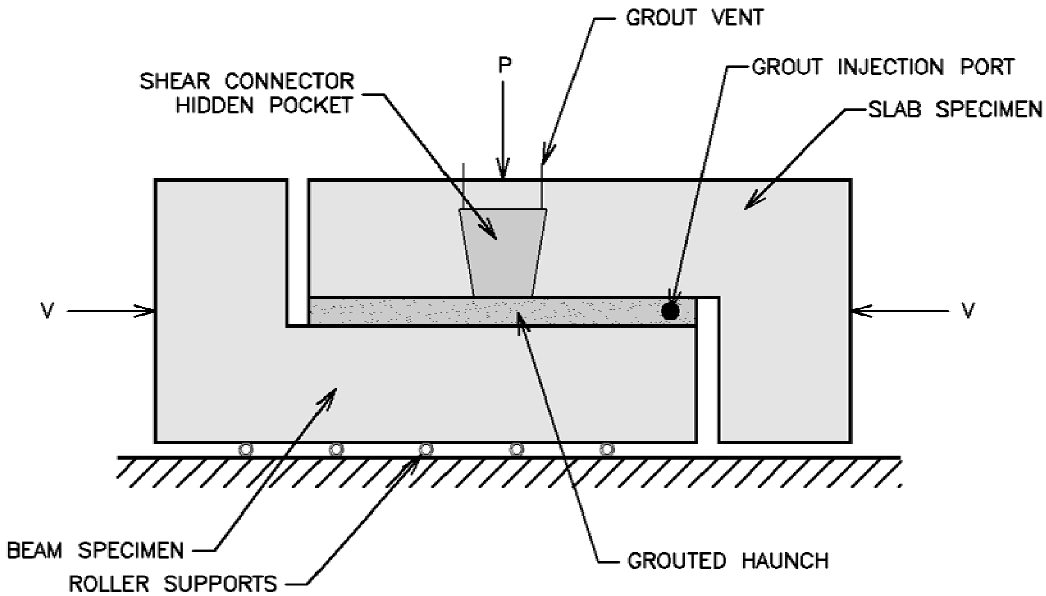


Figure 23. Hidden Pocket Detail

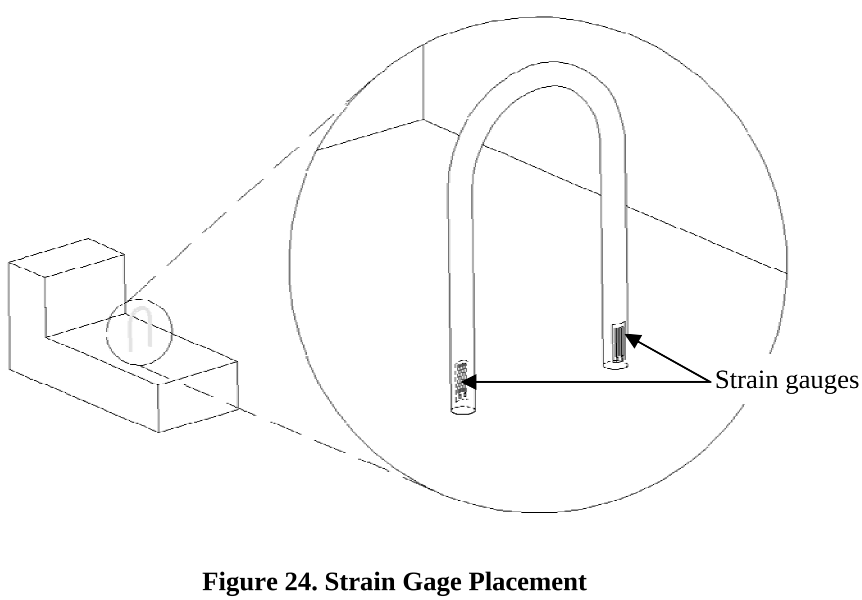


Figure 24. Strain Gage Placement

Test Parameters and Series Details

Within each series, different parameters were varied. A summary of the test series is presented in Table 7. A minimum of two repetitions was performed for each detail. The parameters that were varied included the grout type, the type of connectors, the slab bottom surface treatment and the pocket type. The types of grout used were Five Star® Highway Patch, Set® 45 Hot Weather, and Set® 45 Hot Weather extended with pea gravel. The slab surface treatments were smooth and exposed aggregate.

The connectors used were either double leg stirrups or headed shear studs. The double leg stirrups were either No. 4 bars or No. 5 bars. Arrangements of two, three and four headed shear studs were used. The studs were ¾ in. diameter and 7 in. in length. The headed shear studs were attached to a plate embedded in the beam side specimen. The bottom of the plate had studs attached to properly anchor the plate in the concrete.

Table 7 presents the variables examined in each test series. The individual results from within each series can be found in Wallenfelsz (2006).

Table 7. Horizontal Shear Strength Test Summary

Series	Shear Connector	Grout Type	Surface Treatment	Repetitions	Pocket
1	2 No. 4 bars	Five Star Highway	Exposed Aggregate	2	6 in. cylinder mold
2	2 No. 4 bars	Set 45 Extended	Exposed Aggregate	2	6 in. cylinder mold
3	2 No. 4 bars	Set 45 Neat	Exposed Aggregate	3	6 in. cylinder mold
4	2 No. 5 bars	Set 45 Extended	Exposed Aggregate	2	6 in. cylinder mold
5	2 No. 5 bars	Five Star Highway	Exposed Aggregate	2	6 in. cylinder mold
6	2 No. 5 bars	Set 45 Neat	Exposed Aggregate	3	6 in. cylinder mold
7	2 No. 4 bars	Five Star Highway	Smooth	2	6 in. cylinder mold
8	2 No. 5 bars	Five Star Highway	Smooth	3	6 in. cylinder mold
9	No shear studs	Five Star Highway	Smooth	2	6 in. cylinder mold
10	2 Nelson Studs	Five Star Highway	Smooth	2	6 in. cylinder mold
11	4 Nelson Studs	Five Star Highway	Smooth	2	6 in. cylinder mold
12	3 Nelson Studs	Five Star Highway	Smooth	2	6 in. cylinder mold
13	2 No. 4 bars	Five Star Highway	Exposed Aggregate	2	Hidden Pocket

RESULTS

Compressive Strength: ASTM C 109

Each candidate grout lived up to its claim as a high early strength material. Test results are presented in Table 8 and Figure 25. Most grouts achieved 2000 psi in two hours. ThorRoc 10-60 (1) had the highest compressive strength at each of the one hour, two hour, one day and seven day periods. Set® 45 HW extended (8) and SikaQuick® 2500 extended (6) exhibited the lowest compressive strength for one hour and two hour periods and for one day and seven day periods, respectively. In all cases, the extended grouts did not gain as much strength as the corresponding neat grouts. While these comparative measures are useful, it is more important to examine whether each grout was able to attain a strength at each period that is suitable for a precast deck panel system. Set® 45 HW (4 & 8) displayed its ability to remain workable for a longer period of time, and gained a significant amount of strength by the end of the first day.

Five Star® Patch (3 & 7) displayed a significant strength gain in the second hour. These characteristics could be viewed as attractive, since a one hour strength that is too high could hinder mixing and placement in the field.

Table 8. Compressive Strengths per ASTM C 109

	Grout	Compressive Strength, psi			
		1 hr.	2 hr.	1 day	7 day
1	ThoRoc® 10-60	**2700**	**3030**	**5210**	**6380**
2	SikaQuick® 2500	1700	2250	3540	4710
3	Five Star® Patch	910	2810	5080	5820
4	Set® 45 HW	420	2050	4930	4930
5	ThoRoc® extended	**1860**	2370	3150	5040
6	SikaQuick® extended	1020	1170	1900	2550
7	Five Star® extended	-	**2730**	**4490**	**5440**
8	Set® 45 HW extended	-	230	2650	4180

Bold values indicate the highest values for neat and extended mortars at each time period.

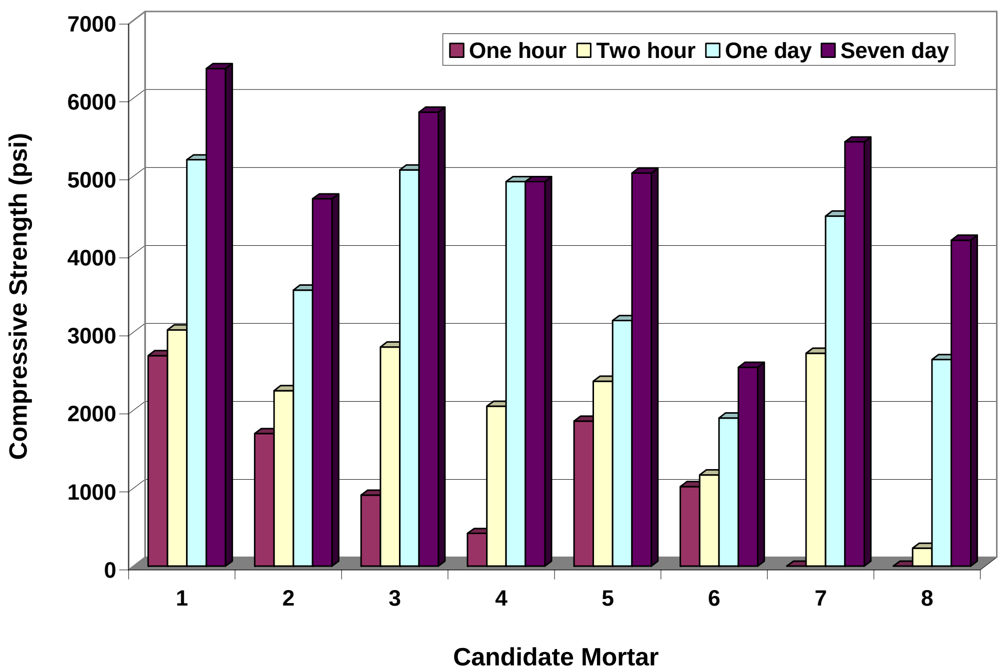


Figure 25. Compressive Strengths per ASTM C 109

Tensile Strength: ASTM C 496

Each candidate grout achieved a 200 psi split tensile strength by one day. Every grout except SikaQuick® 2500 (2 & 6) achieved 400 psi by seven days. Only the ThoRoc® (1) and

Five Star® (3 & 7) products achieved 525 psi by seven days. Test results are presented in Table 9 and Figure 26.

Table 9. Splitting Tensile Strengths per ASTM C 496

	Grout	Tensile Strength, psi	
		1 day	7 day
1	ThoRoc® 10-60	385	**540**
2	SikaQuick® 2500	255	340
3	Five Star® Patch	**485**	530
4	Set® 45 HW	380	410
5	ThoRoc® extended	410	510
6	SikaQuick® extended	280	335
7	Five Star® extended	**445**	**555**
8	Set® 45 HW extended	330	415

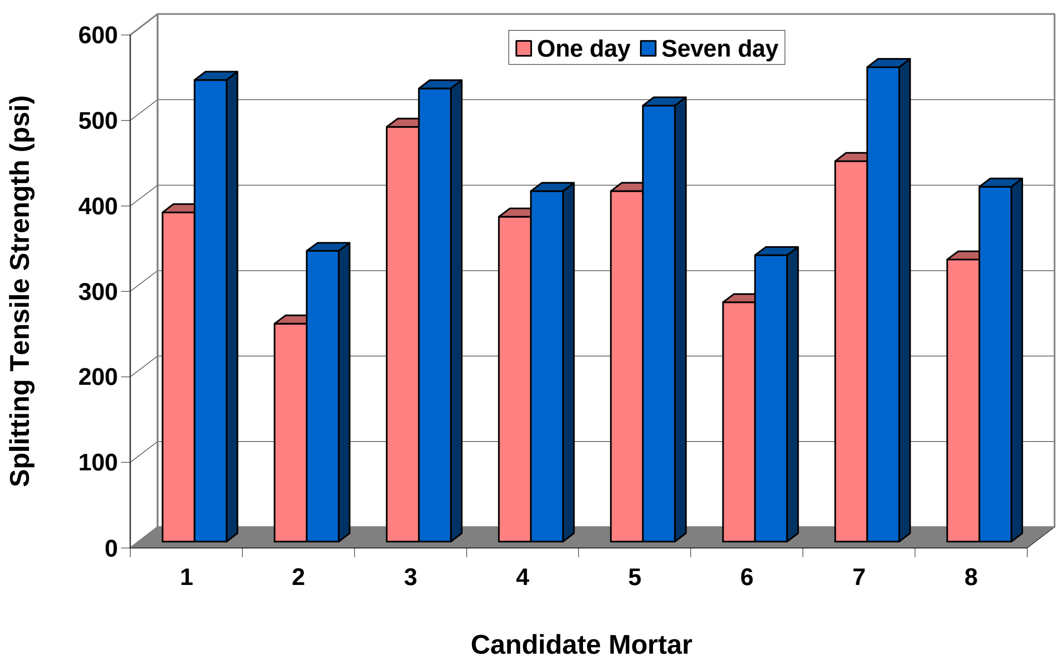


Figure 26. Splitting Tensile Strengths per ASTM C 496

None of the grouts exhibited a significant strength increase between one and seven days, as they all achieved at least 70% of their seven day strength in the first day. The tensile strength of the extended grouts remained fairly consistent with their neat grout counterparts, with seven day strengths varying by 6% at most. They did not consistently display lower tensile strengths as was the case for compressive strength.

Shrinkage

ASTM C 157

Shrinkage was measured periodically for each mortar and concrete for over 500 days. ASTM specifies that neat grouts and extended grouts must be analyzed separately since the shrinkage bars are different sizes. Shrinkage strains for the eight nominally identical concrete mixes are shown in Figure 27. Each concrete batch is associated with the grout of the same number. Typical 28 day shrinkage values for the 4000 psi concrete mix used in this research were between 300 and 400 microstrain, but at 500 days, shrinkage was much higher, between 600 and 800 microstrain. Presented data points are the average of three specimens. Average standard deviation for the concrete shrinkage data was 32με.

Of the eight candidate mortars, Five Star® Patch (3 & 7) and Set® 45 Hot Weather (4 & 8) performed the best, exhibiting a shrinkage of less than 0.04% (400 microstrain) for both the neat and extended grouts at 28 days. The SikaQuick® 2500 (2) bars were especially difficult to remove from the forms, resulting in local cracking. The results for this mortar are displayed with an asterisk (*) since they may not be representative of true shrinkage values. Results for neat grouts are presented in Table 10 and Figure 28, and results for extended grouts are presented in Table 11 and Figure 29. Presented data points are the average of three specimens. Average standard deviation for the grout shrinkage data was 27με.

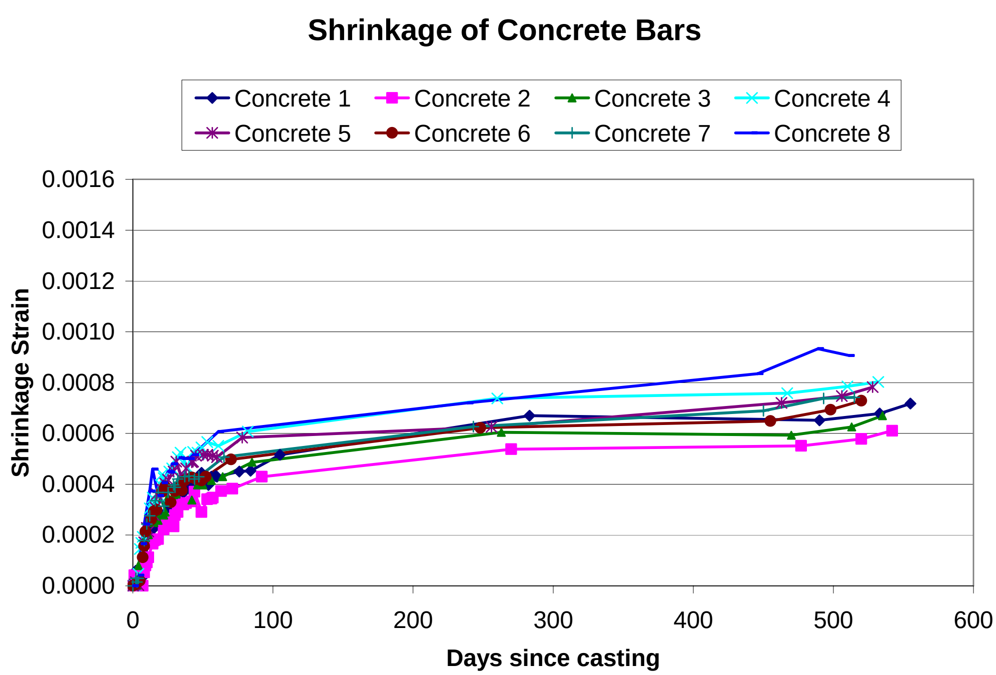


Figure 27. Concrete shrinkage

Table 10. 28 Day Shrinkage for Neat Grouts per ASTM C 157

	Grout	28 Day Shrinkage		
		in.	%	με
1	ThoRoc® 10-60	0.0076	0.076	760
2	SikaQuick® 2500*	0.0080*	0.080*	800*
3	Five Star® Patch	**0.0029**	**0.029**	**290**
4	Set® 45 HW	0.0034	0.034	340

Based on 1 in. x 1 in. x 11 in. shrinkage bars.

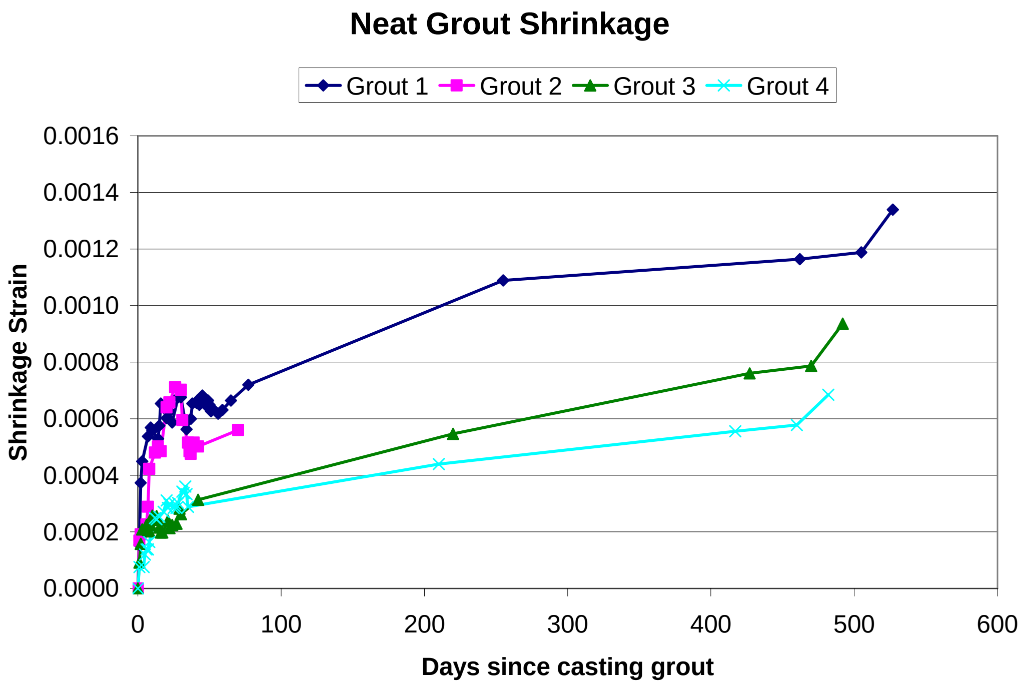


Figure 28. Shrinkage of Neat Grouts per ASTM C 157

Table 11. 28 Day Shrinkage for Extended Grouts per ASTM C 157

	Grout	28 Day Shrinkage		
		in.	%	
5	ThoRoc® extended	0.0064	0.064	640
6	SikaQuick® extended	0.0089	0.089	890
7	Five Star® extended	0.0036	0.036	360
8	Set® 45 HW extended	**0.0018**	**0.018**	**180**

Based on 3 in. x 3 in. x 11 in. shrinkage bars

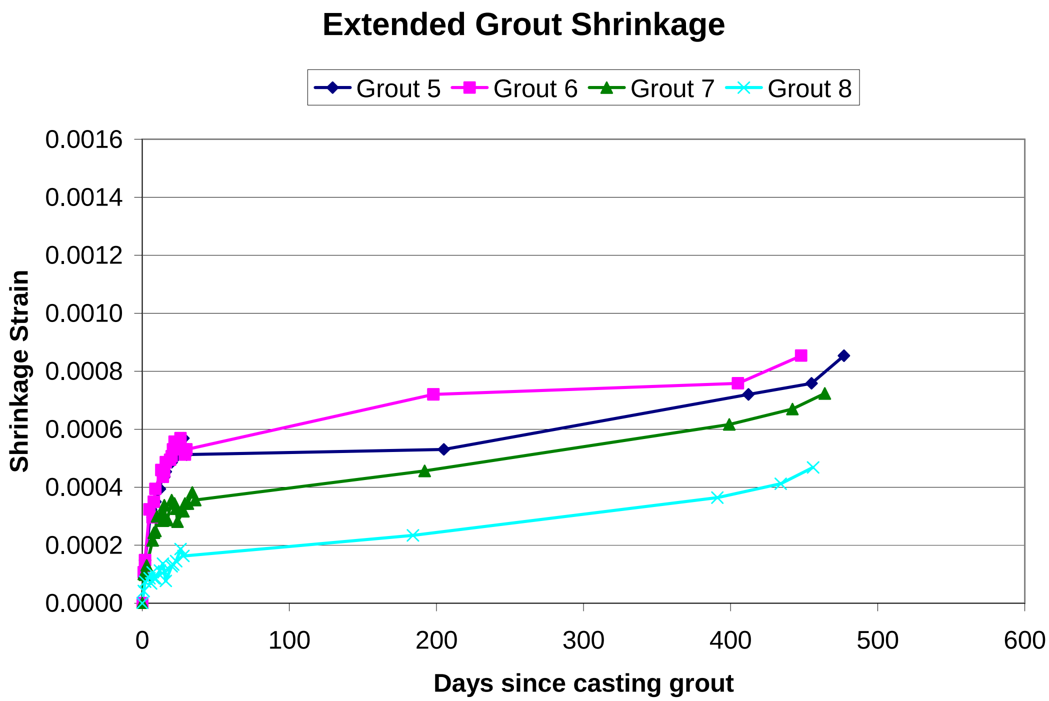


Figure 29. Shrinkage of Extended Grouts per ASTM C 157

Comparisons Between Neat and Extended Grouts

In comparing all of the shrinkage data, the neat grouts for SikaQuick® 2500 (2) and Five Star® Patch (3) displayed less shrinkage than their corresponding extended grouts (6 & 7). This is counter-intuitive. For the same size specimen, an increasing presence of aggregate should result in decreasing shrinkage values because the aggregate tends to restrain the shrinkage of the cement paste. However, two different size specimens were used in this research (1 in. and 3 in.). The different sizes were used because 1 in. is the standard for grout and 3 in. is the standard for concrete. According to W. Morrison, ASTM C 157 technical committee contact person (personal communication, November 2, 2004), ASTM does not supply a method for comparing shrinkage values between different size specimens, but would be interested in developing a specific correlation.

ACI 209R (1992): Prediction of Creep, Shrinkage and Temperature Effects in Concrete Structures presents a unified method for correcting ultimate shrinkage values, $(\varepsilon_{sh})_u$, based on deviations from normal conditions. The variable in this investigation that affects direct comparison of shrinkage between neat and extended grouts is the difference in size of the shrinkage bar specimens. ACI 209R provides two correction factors based on member size; it is up to the designer to decide which to use, but both may not be used together. The first correction factor is based on volume-surface ratio, with 1.5 in. considered standard. The second correction factor is based on a minimum average specimen thickness, with 6 in. considered the minimum. Therefore, if a specimen has a volume-surface ratio other than 1.5 in., or an average thickness less than 6 in., the ultimate shrinkage value, $(\varepsilon_{sh})_u$, may be multiplied by either of the appropriate correction factors. The equations for calculating these correction factors are presented below.

$$\gamma_{vs} = 1.2 \exp(-0.12 \text{ v/s}) \tag{1}$$

where γ_{vs} = volume-surface correction factor
v/s = volume-surface ratio of specimen, in.

$$\gamma_h = 1.23 - 0.038h \tag{2}$$

where γ_h = average thickness correction factor during first year of drying
h = average thickness of specimen, in. (< 6 in.)

The corrected ultimate shrinkage value may then be used in the common time-ratio equation to estimate shrinkage at a given time. For seven day moist cured concrete,

$$(\varepsilon_{sh})_t = \frac{t}{35+t}(\varepsilon_{sh})_u \tag{3}$$

where $(\varepsilon_{sh})_t$ = shrinkage at time t
t = time in days after seven day moist cure period
γ_{sh} = shrinkage correction factor (in this case, either γ_{vs} or γ_h)
$(\varepsilon_{sh})_u$ = ultimate shrinkage value

If specific local information is unavailable, ACI 209R allows an average ultimate shrinkage value of 780 microstrain to be used.

Since the intent is to compare recorded shrinkage values for different size specimens, and not to predict such values, the correction factor shall be used on the right hand side of the equation so that the recorded shrinkage values for each mortar will be divided by the appropriate correction factor. The volume-surface ratio correction factor has been selected to modify the recorded shrinkage values for this research. Volume-surface ratio is calculated per unit length based on the cross section of a given specimen.

For a 1 in. x 1 in. shrinkage bar,
v/s = (1 * 1) / (4 * 1) = 0.25
γ_{vs} = 1.2 exp(-0.12 * 0.25) = 1.165

For a 3 in. x 3 in. shrinkage bar,
v/s = (3 * 3) / (4 * 3) = 0.75
γ_{vs} = 1.2 exp(-0.12 * 0.75) = 1.097

The recorded shrinkage values were divided by the appropriate correction factors in order to compare the normalized values between neat grouts and extended grouts. The corrected values are presented in Table 12.

Table 12. 28 Day Shrinkage with Volume-Surface Ratio Correction Factor

Grout		ΔL, in.	γ_{vs}	Corrected Shrinkage, ΔL / γ_{vs}		
				in.	%	με
1	ThorRoc® 10-60	0.0076	1.165	0.0065	0.0653	653
5	ThorRoc® extended	0.0064	1.097	0.0058	0.0584	584
2	SikaQuick® 2500	0.0080	1.165	0.0069	0.0687	687
6	SikaQuick® extended	0.0089	1.097	0.0081	0.0812	812
3	Five Star® Patch	0.0029	1.165	0.0025	0.0249	249
7	Five Star® extended	0.0036	1.097	0.0033	0.0328	328
4	Set® 45 HW	0.0034	1.165	0.0029	0.0292	292
8	Set® 45 HW extended	0.0018	1.097	0.0016	0.0164	164

Despite the volume-surface ratio correction factor proposed by ACI 209R, SikaQuick® 2500 (2) and Five Star® Patch (3) still displayed less shrinkage than their corresponding extended grouts (6 & 7). While this normalization of shrinkage values did not reverse the trend for SikaQuick® 2500 (2 & 6) and Five Star® Patch (3 & 7), it did provide a more uniform method to directly compare shrinkage between neat grouts and extended grouts that were obtained using different size specimens.

Representative Test: Shear Pocket with Ponding and Differential Shrinkage

It is unlikely that a precast deck panel would be placed on a bridge before it has achieved its specified 28 day strength. Some concrete shrinkage would have already occurred at this time. For a circular interface, the concrete will shrink inward, causing the interface to contract. If the mortar is then poured at 28 days, both the concrete and mortar will be shrinking towards the center of the circular interface, but at different rates. This is illustrated in Figure 30.

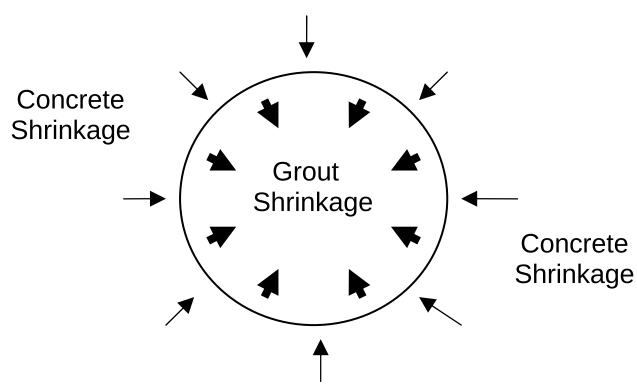


Figure 30. Differential Concrete and Grout Shrinkage at Shear Pocket Interface

To evaluate the difference between the concrete shrinkage and the grout shrinkage, the differences were calculated and plotted. Differential shrinkage, which is the difference in shrinkage values between a grout and the concrete at any time, is presented in Figure 31 for neat grouts and Figure 32 for extended grouts. Each value is computed as follows:

$$\varepsilon_{shdiff}(t) = \varepsilon_{shgrout}(t) - (\varepsilon_{shconc}(t) - \varepsilon_{shconc}(28))$$

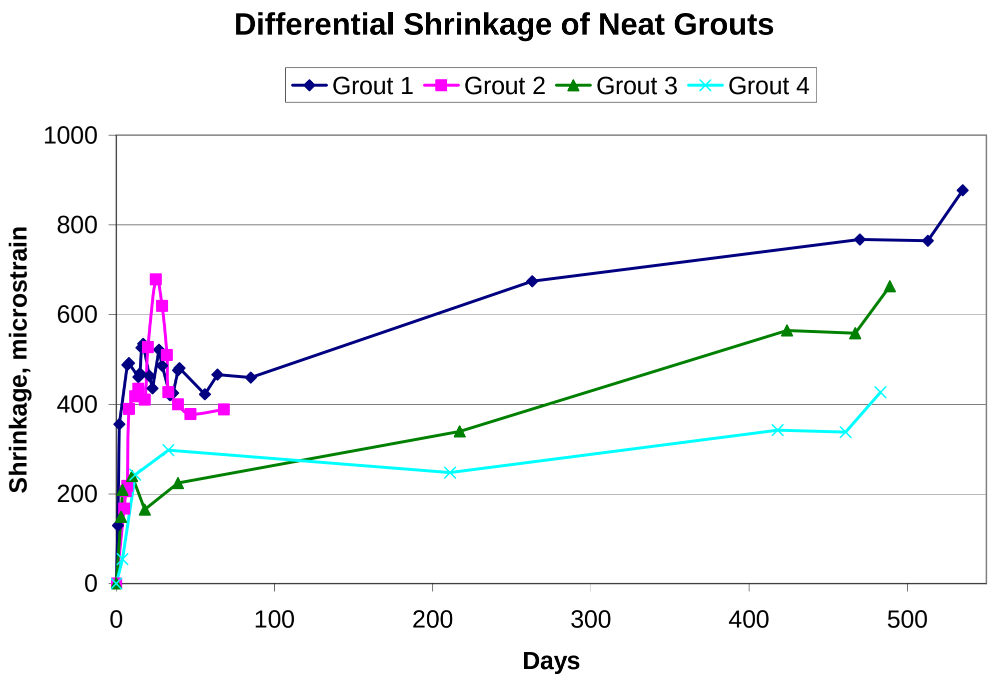


Figure 31. Differential Shrinkage of Concrete and Neat Grouts

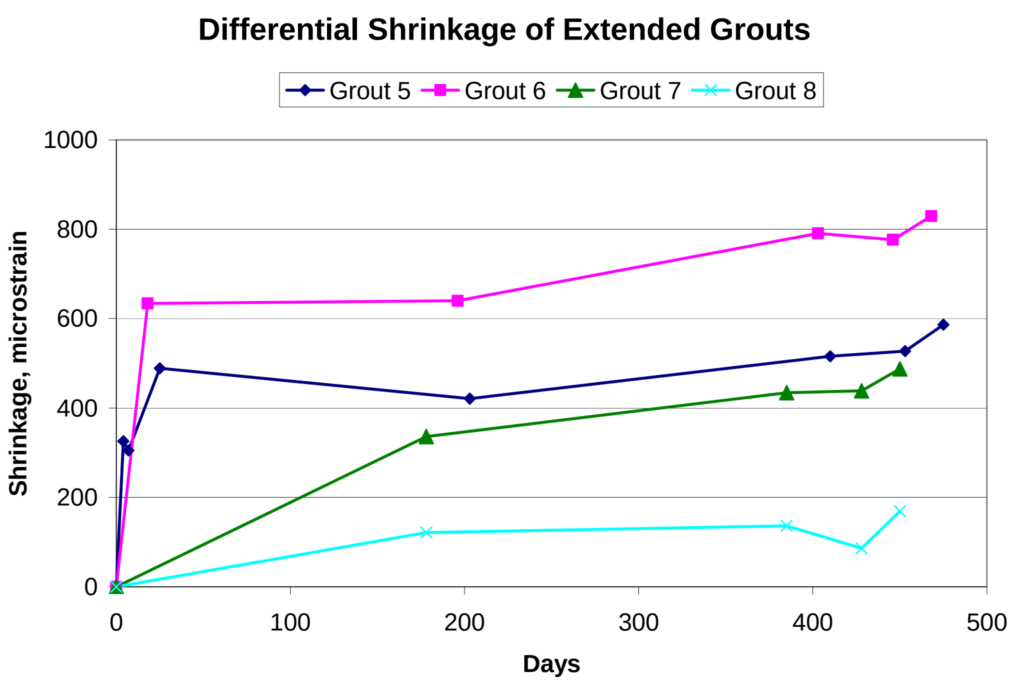


Figure 32. Differential Shrinkage of Concrete and Extended Grouts

The largest differentials between concrete shrinkage and mortar shrinkage were exhibited by ThorRoc 10-60 neat (1) and SikaQuick® 2500 extended (6). Both exhibited differential shrinkages of approximately 800 microstrain at 450 days. The smallest differentials were exhibited by Set 45 HW both neat and extended.

Shear Pocket With Ponding

The shear pocket specimens were ponded with water several times during the first 28 days after placement of the grout, again at 6 months, 12 months and 14 months. The process of ponding consisted of pouring water over the pockets twice a day, once during the morning and once during the afternoon, for a total of two consecutive days. On the third day, the specimens were flipped and checked to see if any water had leaked through at the grout/concrete interface. Pictures and notes were taken in order to document which pockets had leaked.

No specimens showed signs of leaking in the first 28 days. However, some showed evidence of leaking at the 6 month check. The status of the specimens following ponding is summarized in Table 13. Photographs of leaky shear pockets are shown in Figures 33 and 34.

Table 13. Summary of Specimens after Ponding

Grout	Specimen	1 month	6 months	12 months	14 months
1. ThorRoc 10-60 - neat	1A	N	N	N	N
	1B	N	N	N	N
2. SikaQuick 2500 - neat	2A	N	N	N	N
	2B	N	N	N	N
3. Five Star Patch - neat	3A	N	L	L	L
	3B	N	L	L	L
4. Set 45 HW - neat	4A	N	L	L	L
	4B	N	L	L	L
5. ThorRoc 10-60 - extended	5A	N	N	N	N
	5B	N	N	N	N
6. SikaQuick 2500 - extended	6A	N	N	N	N
	6B	N	N	N	N
7. Five Star Patch - extended	7A	N	L	L	L
8. Set 45 HW extended	8A	N	L	L	L

L=leak, N=no leak

Figure 33. Five Star® Patch Neat (3) Shear Pocket Showing Water Leaking at 12 Months

Figure 34. Set® 45 HW Extended (8) Showing Dampness and Efflorescence at 12 Months

Possible Reason for Leaking

Comparing the differential shrinkage presented in Figures 31 and 32 and the leaking pockets listed in Table 13 result in an unexpected observation. The grouts that developed the least amount of differential shrinkage were discovered to be leaking at the six month check. It was assumed that the grouts with the highest differential shrinkage would have the greatest tendency to crack. However, this was not the case since, as can be seen from the Figures 31 and 32, Five Star® Patch neat (3), and Set® 45 HW neat (4) show less differential shrinkage than the other neat grouts, but exhibit leaking. The same is true for the extended grouts Five Star® Patch extended (7) and Set® 45 HW extended (8) show less differential shrinkage than the rest, but are the grouts that leak. From this observation it can be surmised that differential shrinkage is not solely responsible for the leaking.

If the differential shrinkage was not the sole cause of the cracks that were allowing water to leak through the specimens, then there must be another reason the cracks developed. One possible reason could be that the adhesion between the grouts and the concretes was poor, therefore allowing cracks to develop at lower tensile stresses. In order to study the adhesion between grouts and concretes, a series of specimens was devised and pull-off tests were performed as describe earlier. The results are presented in a subsequent section.

Flow and Workability

Observations were made regarding the workability of each candidate grout based on the degree of effort required to mix each product as well as their work time and initial set time. Work time was measured from the start of mixing until workability began to decrease. Decreased workability is defined by the inability to move the grout with vibration, or easily finish a surface. Initial set time was measured from the start of mixing until the product showed resistance to the penetration of a thin rod or trowel edge. The product had attained its initial hardened state at this time. This information, along with observations regarding each product's consistency as well as their performance in the haunch flow mockup representative test, is presented in Table 14. Flow results from the ASTM C 1437 (2001) truncated flow cone tests are presented in Table 15 and Figure 35.

Table 14. Candidate Grout Workability Observations

Grout		Work Time, min.	Initial Set Time, min.	Consistency	Haunch Flow Observation
1	ThoRoc® 10-60	8	16	Thick	poor
2	SikaQuick® 2500	15	24	Medium	good
3	Five Star® Patch	18	30	Medium	good
4	Set® 45 HW	**28**	**44**	Runny	**very good**
5	ThoRoc® extended	10	19	Thick	fair
6	SikaQuick® extended	21	29	Medium	**good**
7	Five Star® extended	15	26	Thick	fair
8	Set® 45 HW extended	**24**	**35**	Medium	**good**

Work Time is the time from when mixing begins until workability begins to decrease.
Initial Set Time is the time from when mixing begins until the grout resists penetration of a thin rod.

Table 15. Truncated Flow Cone Spread Values per ASTM C 1437

Grout		Initial		After 10 Drops		Total Diameter Increase, %
		Average Spread, in.	Diameter Increase, %	Average Spread, in.	Additional Diameter Increase, %	
1	ThoRoc® 10-60	7	75	**10**	43	**150**
2	SikaQuick® 2500	7	75	9.5	36	138
3	Five Star® Patch	**10**	150	**10**	0	**150**
4	Set® 45 HW	9.5	138	**10**	5	**150**
5	ThoRoc® extended	5	25	8.5	70	113
6	SikaQuick® extended	6.5	63	8.5	31	113
7	Five Star® extended	5	25	8.5	70	113
8	Set® 45 HW extended	**7.5**	88	**9**	20	**125**

Initial Flow Cone Diameter = 4 in.

ThoRoc® 10-60 (1) was difficult to mix and had a short set time. Although its flow cone results were favorable, it did not flow well through the haunch. Its very high one hour strength compromised its ability to flow because the grout achieved its initial set too quickly. When the grout failed to emerge from the haunch, the remainder was poured down the opposite pocket to see if a two directional flow could sufficiently fill the space. As expected, this procedure did not give good results as two air pockets were formed as seen in Figure 36. This reaffirmed the importance of pouring grout in one direction in a precast bridge deck panel system, rather than working inward from two points.

ThoRoc® 10-60 extended 50% (5) was also difficult to mix and did not perform as well on the drop table as the neat grout (1). However, since the aggregate extension prolonged the grout's set time and reduced the one hour compressive strength, it remained workable for a longer period of time and, therefore, flowed slightly better through the haunch. However, the flow was still undesirable because it was very slow and the grout did not completely fill the corners or rise into the adjacent shear pocket. Photographs of the haunch flow test for ThoRoc® extended (6) can be found in Scholz (2004).

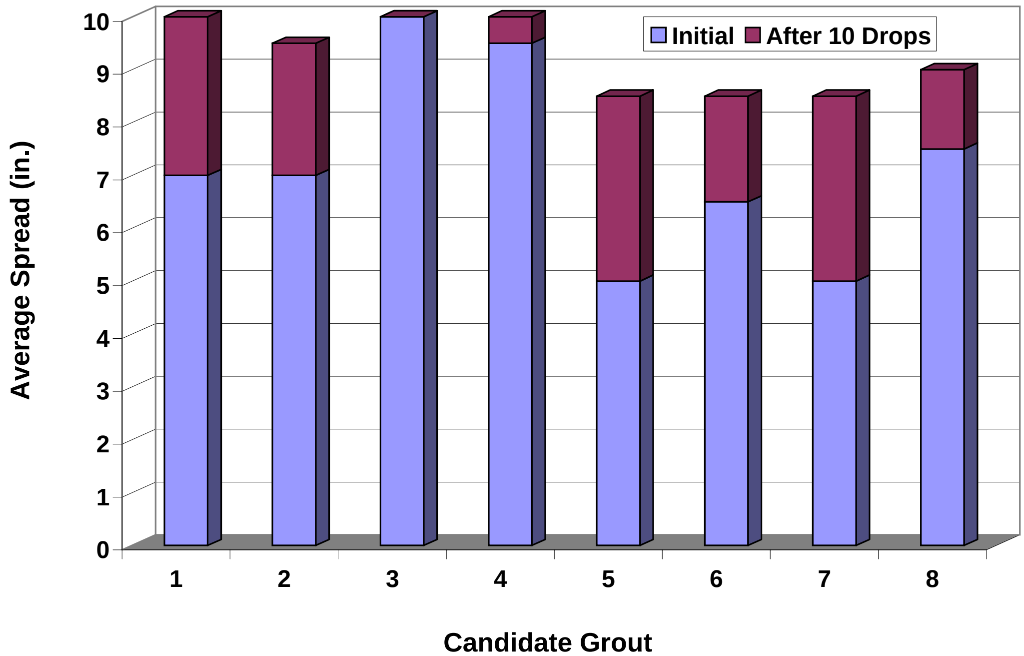


Figure 35. Truncated Flow Cone Spread Values per ASTM C 1437

Figure 36. ThoRoc® 10-60 (1) Flow Through Haunch Mockup

SikaQuick® 2500 (2) was easy to mix, displayed good flow cone results and flowed well through the haunch. While its flow cone performance was almost identical to the ThoRoc® 10-60 (1), its work time was longer and its one hour compressive strength lower, enabling it to flow for a longer period of time. SikaQuick® 2500 extended 50% (6) was fairly easy to mix and flowed almost as well as the neat grout (2). One observation from all of the extended grouts is that they had difficulty filling the sharp corners at the end of the haunch mockup. This should not be a problem in a precast deck panel system because the haunch is continuous along the length of the beam and such end corner conditions are uncommon. Photographs of the haunch flow tests for both SikaQuick® 2500 mortars (2 & 6) can be found in Scholz (2004).

Five Star® Patch (3) was easy to mix and spread over the entire area of the drop table under its own weight. It flowed easily through the haunch. Of all the candidate grouts, its light color best matched the color of concrete. This is a good characteristic because blending in with the concrete deck panel can reduce the patchwork appearance of the riding surface if an additional wearing surface is not applied to the deck. Five Star® Patch extended 80% (7) was almost impossible to mix with such a high recommended aggregate extension. Its flow suffered because of this, but its strength gain was surprisingly similar to the neat grout (3). A lower aggregate extension ratio would certainly be more suitable for use in a precast deck panel system.

Set® 45 Hot Weather (4) was extremely easy to mix and flowed very well on the drop table and through the haunch (see Figure 37). Compared with all candidate grouts, it remained workable for the longest period of time. Aesthetically, its dark color does not match the concrete at all. Set® 45 Hot Weather extended 60% (8) was initially difficult to mix with a high aggregate extension, but as the powder was added, it achieved a consistency similar to that of the neat grout (4). It did not flow as well as the neat mortar (4) but did flow the best of all of the extended candidate grouts. Photographs of the haunch flow test for Set® 45 HW extended (8) can be found in Scholz (2004). The ability to perform well in high temperature conditions is a very attractive feature of Set® 45 Hot Weather. The prolonged work time can also be taken advantage of in normal temperature conditions.

Figure 37. Set® 45 Hot Weather (4) Flow Through Haunch Mockup

Bond Strength

ASTM C 882

Slant shear cylinder tests provided a method of examining each candidate grout's ability to bond to concrete with various types of surface preparations. Two modes of failure were common in these tests:

1) clean shearing of grout/concrete bond along slanted interface (Figure 38a)
2) grout and/or concrete cracking before interface bond failure
   a) grout cracking was not too severe and it was possible to load the specimen until the bonded interface failed (Figure 38b)
   b) grout cracked and split in a vertical manner so that it was not possible to continue loading the specimen (Figure 38c)

Figure 38. Slant Shear Cylinder Failure Modes

In each case, the maximum load was recorded and converted to stress by dividing by the elliptical area of the bonded interface. For a 4 in. by 8 in. cylinder sliced at a 30^o angle, the interface is a 4 in. by 8 in. ellipse and the area is $\pi*(4/2)*(8/2) = 25.13$ in^2. ASTM suggests reporting the results of these tests simply as load divided by area. However, the objective of using this test in this research is to investigate shear stress. Therefore, the maximum load was multiplied by the cosine of 30^o to obtain the true shear stress component acting along the bonded interface. Results for the slant cylinder tests are presented in Table 16 and Figure 39.

Table 16. Slant Cylinder Bond Strength with Varying Concrete Surface Preparations

Grout		Shear Stress with Varying Surface Preparation, psi			
		Smooth	**Exposed Aggregate**	**Raked**	**Raked and Sand Blasted**
1	ThoRoc® 10-60	*540*	*540*	*630*	***650***
2	SikaQuick® 2500	1240	**1400**	1190	670
3	Five Star® Patch	950	**1810**	1540	*720*
4	Set® 45 HW	*520*	*470*	***630***	*560*
5	ThoRoc® extended	1490	**1730**	1320	1450
6	SikaQuick® extended	**980**	850	750	730
7	Five Star® extended	1380	1680	1210	**1700**
8	Set® 45 HW extended	500	**950**	640	820

Values in *italics* represent significant mortar cracking associated with failure mode 2.

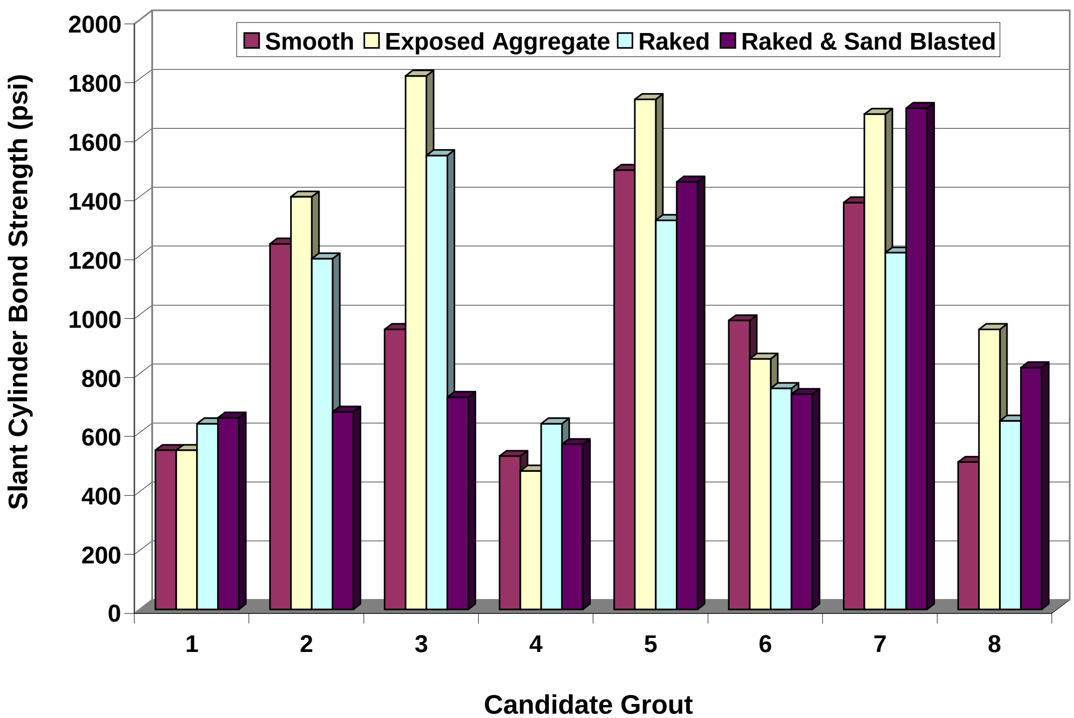


Figure 39. Slant Cylinder Bond Strength with Varying Concrete Surface Preparations

Of all candidate grouts, Five Star® Patch (3) displayed the highest bond strengths for exposed aggregate and raked surfaces, while Five Star® Patch extended (7) and ThoRoc® 10-60 extended (5) displayed the highest bond strengths for raked/sand blasted and smooth surfaces, respectively. Generally, the extended grouts performed slightly better than the neat grouts. The exposed aggregate preparation provided the best bonding surface for four of the eight grouts and was second best for two grouts. The smooth interface performed slightly better than anticipated, providing the worst or second worst bond strength for only half of the candidate grouts. With such a featureless surface, the smooth interface was expected to provide the least bond strength for each grout.

Whether sand blasting would increase the bonding performance of a raked surface was of particular interest in these tests. Only for Five Star® Patch extended (7) did the raked and sand blasted surface display a significant advantage over the raked surface. The raked surface displayed a much higher bond strength than the raked and sand blasted surface for SikaQuick® 2500 (2) and Five Star® Patch (3). However, for the other five candidate grouts, the two surface preparations displayed very similar bond strengths. So while it is possible for sand blasting to increase the bonding capability of a raked concrete surface, it has shown to be ineffective in almost 90% of these tests. For the trouble and cost that is involved with sand blasting, it may not be a worthwhile venture if the concrete surface is already raked.

Push-Off Tests

Based on the performance of the candidate grouts in the property specific tests, three were selected for further investigation through a series of push-off tests. The objective was to form a correlation between slant shear cylinder tests and performance of the grout in horizontal shear at the beam/deck panel interface. Five Star® Patch (3) and Set® 45 HW (4) were selected based on their excellent constructability and shrinkage performance as well as their ability to gain strength quickly after the first hour. The slant shear cylinders for Five Star® Patch (3) performed much better than the Set® 45 HW (4), which should predict a better performance in the push-off tests. Set® 45 HW extended (8) was selected based on its overall performance as the best extended grout. Additionally, this same grout (8) was used in push-off tests by Menkulasi (2002), so comparisons could be made regarding how well the grout fared in the two different push-off test configurations. With the exposed aggregate and raked surfaces performing best in the slant shear cylinder tests, it was decided to use these preparations for the push-off test specimens. The beam side was given a raked finish and the slab side was given an exposed aggregate finish. Menkulasi used the same surface preparations for his push-off tests because it had been recommended by a precaster. Two push-off tests were conducted for each of the three grouts.

Results of the push-off tests are presented in Table 17. Clamping stress is defined as the sum of the applied normal force and the force provided by the steel reinforcement divided by the area of the interface. Since there was no steel reinforcement crossing the interface, the clamping stress is simply the vertical load, P_n, divided by the interface area, $b_v s$.

Table 17. Push-Off Test Results

	Grout		**V_{peak}, lb**	**P_n, lb**	**A_{cv}, in^2**	**v_{peak}, psi**	**cl, psi**	**Slip, in.**	**Failure Plane**	**f'$_c$, Grout, psi**	**f'$_c$, Conc., psi**
3	Five Star® Patch	A	33500	3850	424	79.0	9.1	0.0091	slab	4480	3830
		B	35600	4700	316	112.7	14.9	0.0153	slab	4480	3830
4	Set® 45 HW	A	43200	3420	424	101.9	8.1	0.0078	beam	3780	3830
		B	42700	2500	424	100.7	5.9	0.0096	beam	3780	3830
8	Set® 45 HW ext.	**A**	**50500**	4050	424	**119.1**	9.5	0.0178	beam	3780	3830
		B	44000	2700	424	103.8	6.4	0.0149	beam	3780	3830

V_{peak} = shear load at failure, lb
P_n = normal force at failure, lb
$A_{cv} = b_v s$ = area of interface, in^2
v_{peak} = shear stress at failure, psi
cl = clamping stress at failure, psi
slip = maximum slip at failure, in.

Set® 45 HW extended (8) provided the highest shear resistance along the interface, followed by Set® 45 HW (4) and then Five Star® Patch (3). In each case, the specimen was not able to sustain much or any load after the bond failure. The load-slip plots are presented in Figure 40.

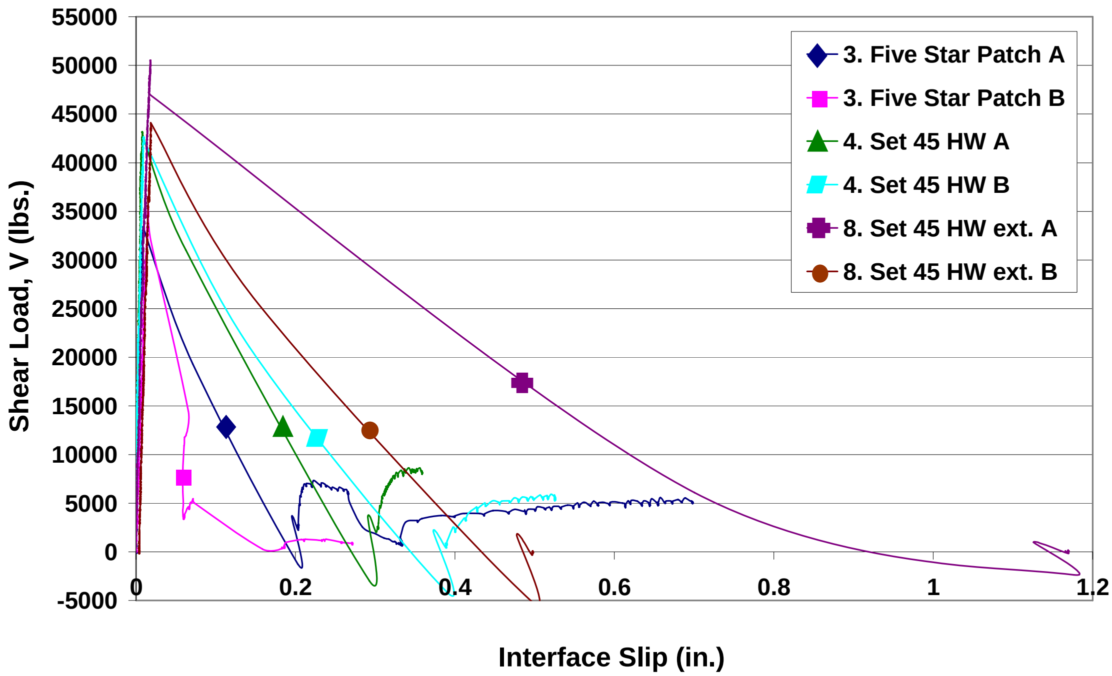


Figure 40. Push-Off Test Shear Load vs. Interface Slip

Correlations Between Slant Shear Cylinder Tests and Push-Off Tests

Five Star® Patch (3) exhibited the best interface bond in the slant cylinder tests, but fared worst of the three grouts used in the push-off tests. Also, the slant cylinders did not correctly predict whether the beam/grout interface or the slab/grout interface would fail in the push off tests. For Five Star® Patch (3), the slant cylinders displayed a higher bond with an exposed aggregate concrete finish, but the push-off tests failed along the exposed aggregate surface of the slab-side specimen. Both Set® 45 HW (4 & 8) slant cylinder tests showed similar results for the exposed aggregate and raked finish. However all of the push-off tests failed along the raked beam interface. The slant shear cylinder tests did not accurately predict the outcome of the push-off tests. Individual slant cylinder tests were tabulated in a similar fashion to the push-off test results and then plotted along with the push-off test points on the shear stress versus clamping stress graph. Shear stress and clamping stress for the slant cylinders are simply the components of the compressive force, F, which act along the bond interface (Fcos(30^{o})) and normal to the bond interface (Fsin(30^{o})), respectively. These values are presented in Table 18. Note that Table 18 presents individual test results, averages are presented in Table 16. Figure 41 illustrates that the horizontal shear resistance for the slant cylinder tests were not in the range of the push-off tests. Also shown in Figure 41 are equations formulated by Menkulasi to calculate horizontal shear strength at a grouted haunch. The plot also illustrates the high variability in test results on bond strength and adhesion.

Table 18. Individual Slant Shear Cylinder Test Results for Each Grout

	Grout	Cylinder	Load, lb	V_{peak}, lb	P_n, lb	A_{cv}, in^2	v_{peak}, psi	cl, psi	f'$_c$ Grout, psi
3	Five Star® Patch	Raked 1	45500	39404	22750	25.13	1567.8	905.2	5080
		Raked 2	44000	38105	22000	25.13	1516.2	875.4	5080
		Ex. Agg. 2	52550	45510	26275	25.13	1810.8	1045.5	5080
4	Set® 45 HW	Raked 1	17500	15155	8750	25.13	603.0	348.2	4930
		Raked 2	17500	15155	8750	25.13	603.0	348.2	4930
		Raked 3	20000	17321	10000	25.13	689.2	397.9	4930
8	Set® 45 HW ext.	Raked 1	19500	16887	9750	25.13	671.9	387.9	3230
		Raked 2	18500	16021	9250	25.13	637.5	368.1	3230
		Raked 3	17500	15155	8750	25.13	603.0	348.2	3230

Terms as defined in Table 17

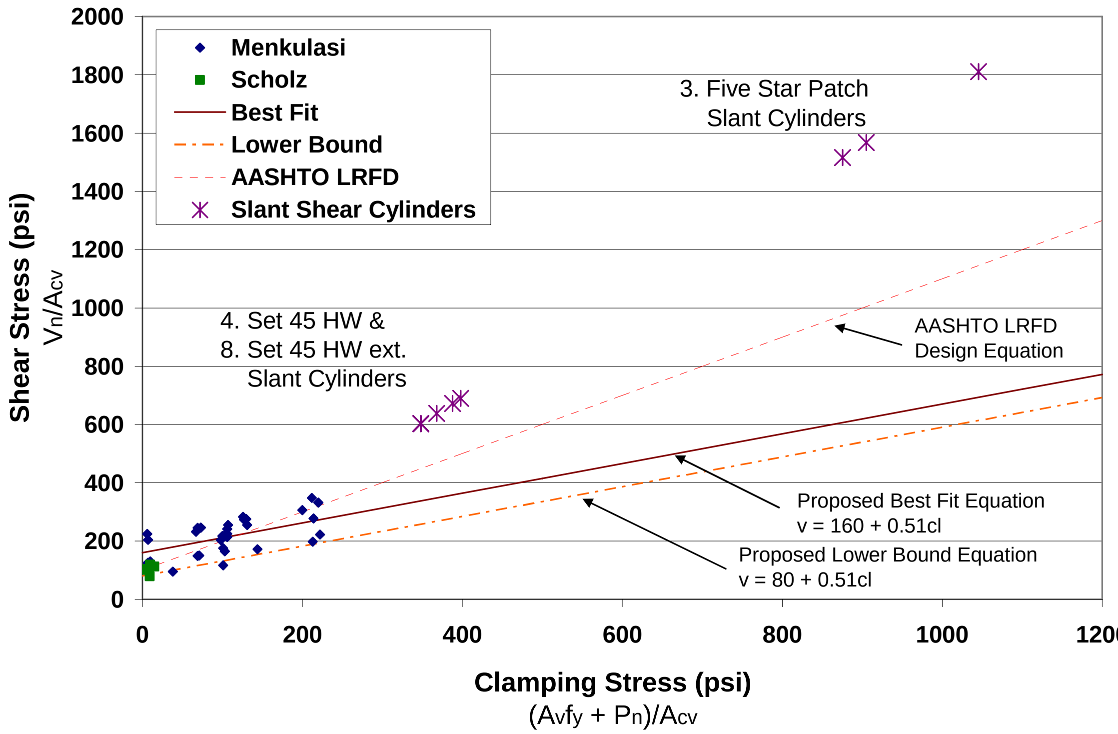


Figure 41. Shear Stress vs. Clamping Stress with Slant Shear Cylinders

Since the shear stress and clamping stress for the slant cylinder tests are purely a function of their geometry, the results will always plot along a line with a slope of cos(θ)/sin(θ) and a y-intercept of 0; in these tests, the slope of the line is $\cos(30^o)/\sin(30^o) = 1.732$. One possible means of better correlating slant shear cylinder tests to push-off tests would be to prepare cylinders with three different slant geometries, for instance, 30, 45 and 60 degrees. The results of these three tests could be plotted on the same shear stress versus clamping stress plot and a best fit line could be established. If the slope of that line resembled the general trend of push-off tests, even with a different y-intercept, the two tests could be correlated with a ratio of the slopes.

Adhesion Test Results

Smooth Dry Surface

In this test, the PVC molds were taken off before gluing the steel caps to the grout discs. This was done so that the adhesion of the Silicon caulk, which held the molds in place during grout placement, would not affect the overall pull-off loading. The results from these tests, did not show a consistent relationship between the neat grouts, and their corresponding extended versions (see Figure 42). However, the adhesion of the neat and extended grouts was similar for grouts 1 and 4, and grouts 2 and 5. Grout 3, the neat version, had much higher adhesion than grout 7, the extended version, while grout 4, the neat version, had lower adhesion than grout 8, the extended version. An interesting observation is that grouts 3 and 8 showed the highest adhesion and relatively low differential shrinkage, but both developed cracking and leaking in the shear pocket ponding tests.

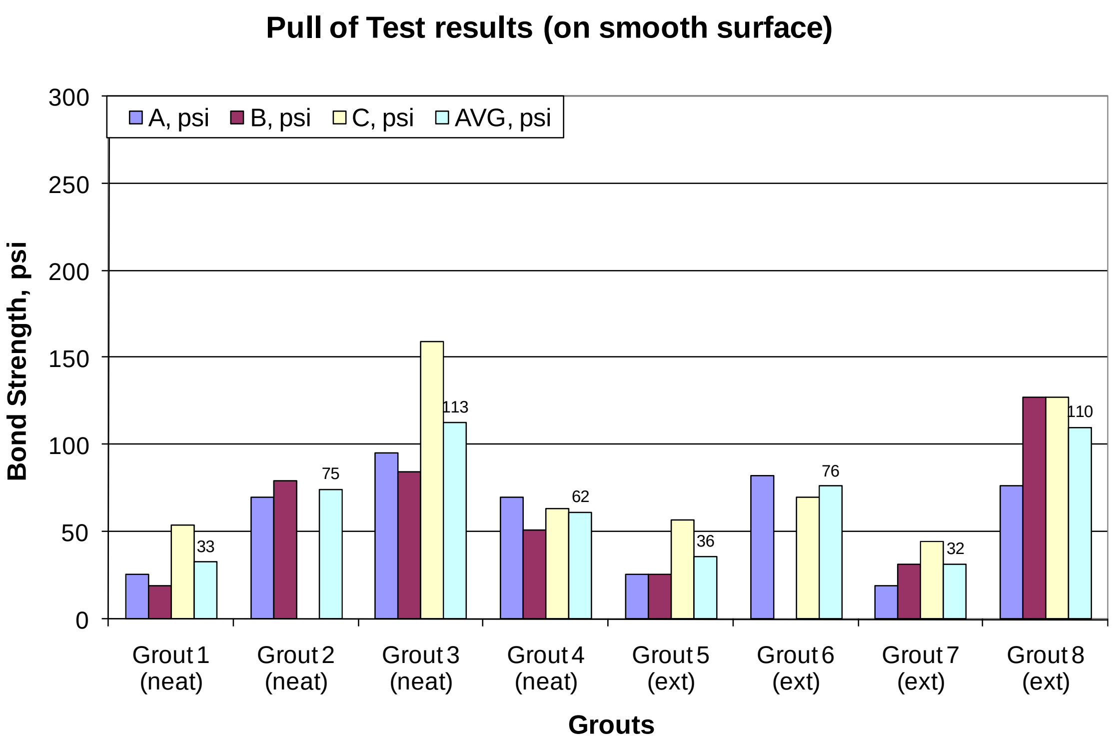


Figure 42. Results from Pull-off Tests Performed on Smooth Dry Surface

It should be noted that taking the PVC forms off was very difficult and pulling/pushing the forms out could have reduced the adhesion which altered the results. Since the grout discs were very small, any movement along the slab such as moving the mechanical device around could have caused vibrations which could have had an effect on the results. Some loadings had to be left out from the data because they were outliers. These resulted from accidentally hitting the grout discs with the device as it had to be moved around a lot.

Smooth Saturated Surface Dry Surface

In this test, the PVC forms were not taken off in order to have less variable results. The amount of loading that it took for the Silicon caulk glued PVC molds to pull off was measured in order to get an idea of how much this may affect the results. This was found to be 50 lb, which is very small compared to the total pull-off force. The results found in this series showed a stronger correlation between the neat and extended grouts as was expected (see Figure 43). However, although these results seem to be more accurate they still showed that the leaky grouts (3, 4, 7, and 8) had some of the strongest adhesion found.

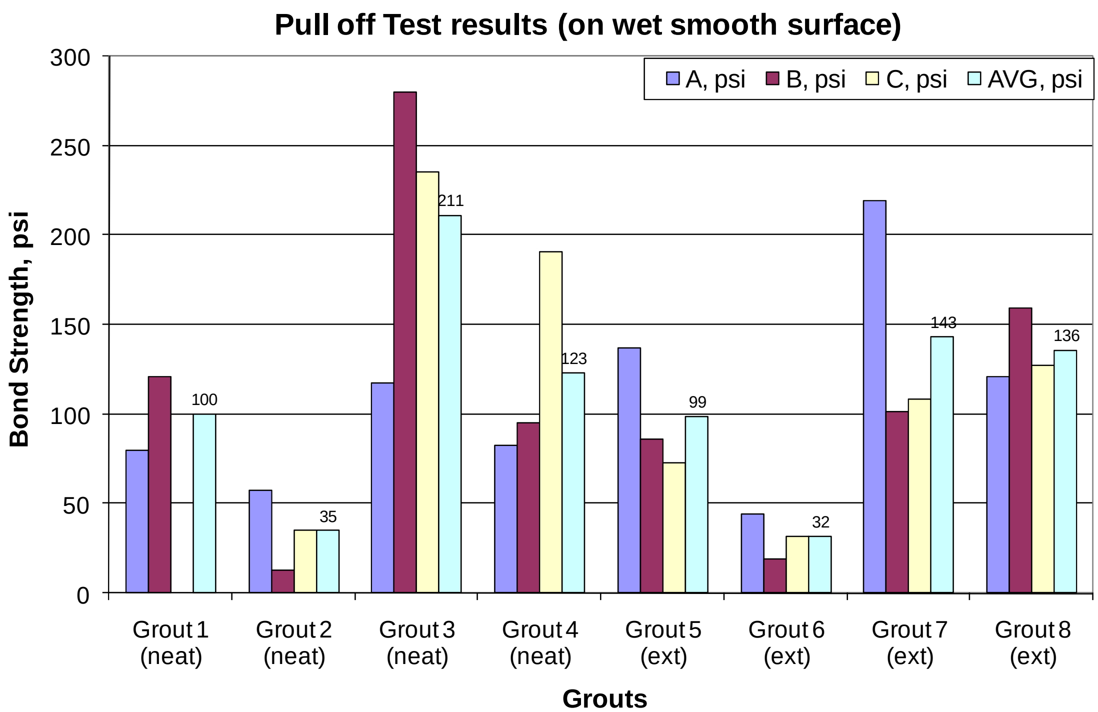


Figure 43. Results from Pull-off Tests Performed on Smooth Saturated Surface Dry Surface

Smooth, Sand-Blasted, Saturated Surface Dry Surface

In this test, the concrete slab was sand blasted to investigate if this surface treatment would produce higher cohesion values between the grouts and concrete. As was done in the previous set of tests, the PVC forms were not removed from the grout discs after they had cured. The grouts were poured within a few hours after the slab was sand blasted. Figure 44 shows the results from this test. Note that only grout 2 showed an improvement in adhesion from sand blasting.

Figure 45 summarizes all of the adhesion tests. Typical adhesion strengths were between 30 and 140 psi. Wetting the surface increased adhesion significantly, but sand blasting and wetting did not result in significantly higher adhesion than simply wetting the surface.

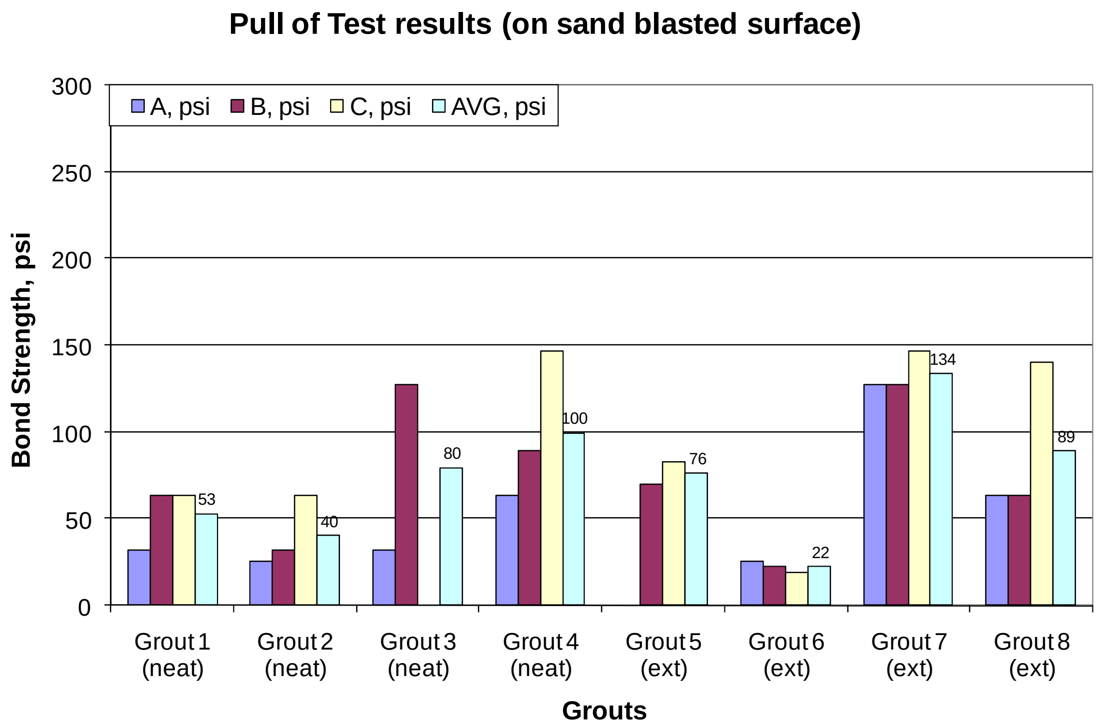


Figure 44. Results from Pull-off Tests Performed on Sand-blasted Smooth Wet Surface

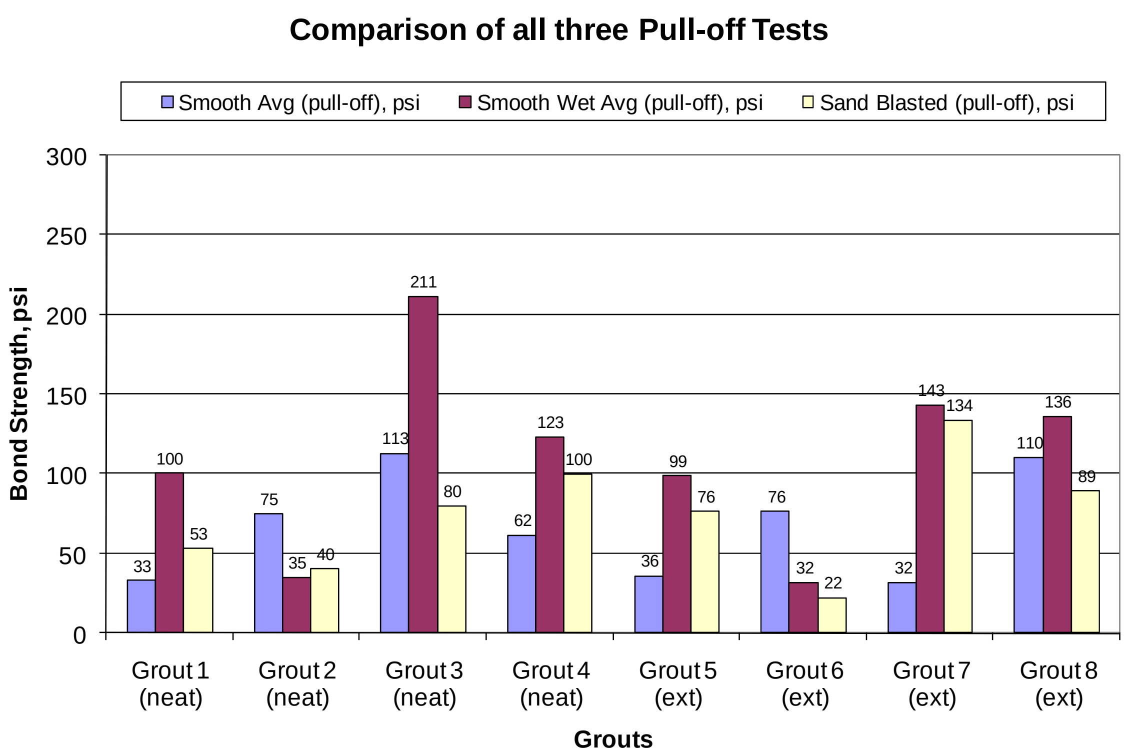


Figure 45. Comparison of All Pull-off Tests Results

Neither the differential shrinkage nor the adhesion between the grouts and concrete were found as the answer to why grouts 3, 4, 7, and 8 developed cracks and leaked. This study proved that these grouts had the lowest differential shrinkage and had some of the highest adhesion among all the samples, yet still leaked.

Results of Horizontal Shear Strength Tests

To investigate the horizontal shear capacity of the precast deck panel system, push-off tests were performed. From the data collected during push off tests, plots of horizontal load versus relative slip were produced. The plots can be broken down into three categories. A typical push off test load versus slip plot of each category can be seen in Figure 46. As the un-cracked specimen is loaded horizontally, the load increases with little slip until a crack is formed. This crack was typically found at the top interface between the slab and the haunch rather than the bottom interface between the beam and the haunch. This can be seen in Figure 47. However, this was not true of the headed shear Stud specimens.

As seen in Figure 46(a) when the horizontal shear resistance of the shear connectors is less than the resistance due to cohesion the load has a sharp drop following cracking of the interface. Then, an approximately constant load is maintained. When the horizontal shear resistance of the connectors is approximately equal to the cohesion a small sudden drop is seen as the crack is formed then the sustained load is about equal to the peak load. This can be seen in Figure 46(b). If the horizontal shear resistance of the shear connectors is greater than the cohesion, a different behavior can be seen as in Figure 46(c). As in the other cases the load is increased as the relative slip remains low then as a crack at the interface forms, load is transferred from cohesion to the shear connectors. This can be seen where the slope changes. Then a peak load is reached where the connectors begin to yield. Beyond that point the sustained load is slightly lower than the peak load.

Most previous research that investigated push-off tests and horizontal shear strength was for cast-in-place slab systems. When these specimens were prepared, concrete was cast on concrete. For this research there is a haunch that is grouted and the tests have shown that the casting orientation is significant. Menkulasi (2002) performed push off tests that included a haunch, but grouted them while they lay on their side. A more accurate method, which is more representative of the way precast panels are grouted, is with the beam side on the bottom and slab side on the top. The grout is then poured down through the shear pocket. Grouting the haunch with the specimens on their sides causes the cohesion and friction to be larger than would be after field grouting operations. This reduced cohesion and friction is a result of air trapped at the top interface between the haunch and slab, as shown in Figure 48.

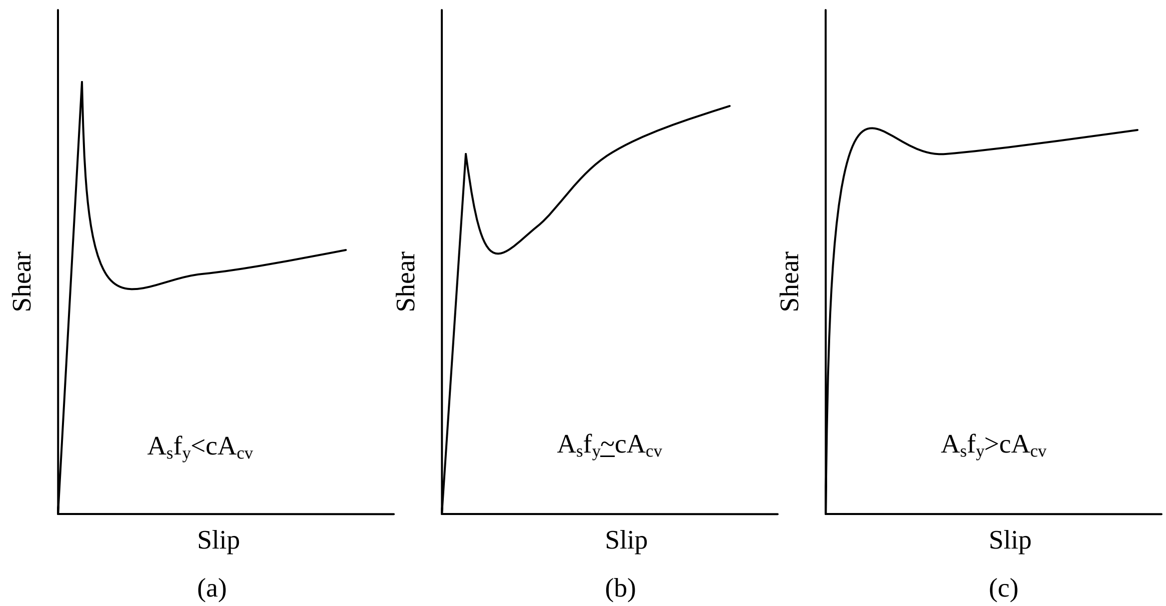


Figure 46. Typical Load vs. Slip Plots

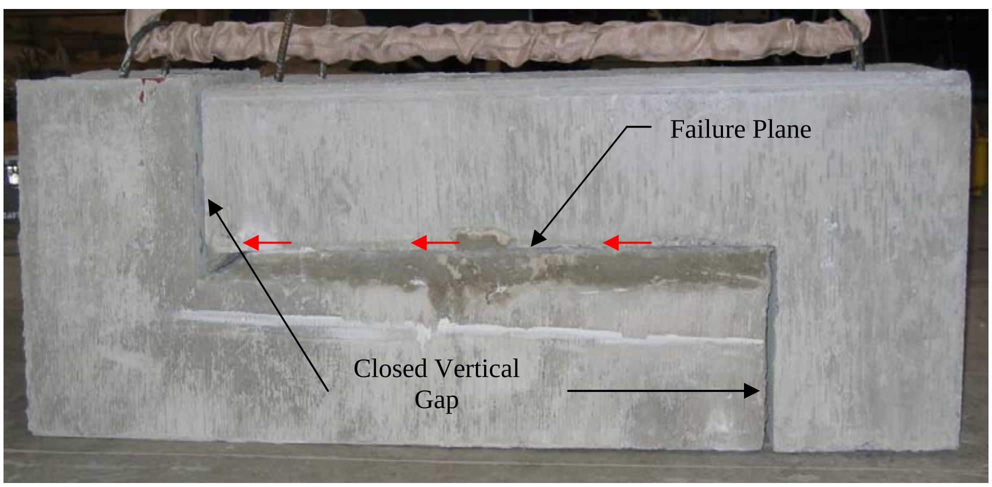


Figure 47. Push-Off Specimen after Failure

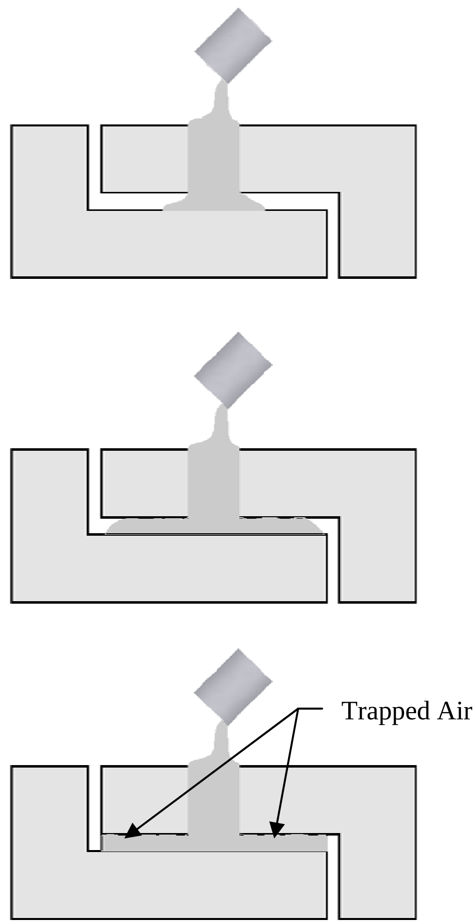
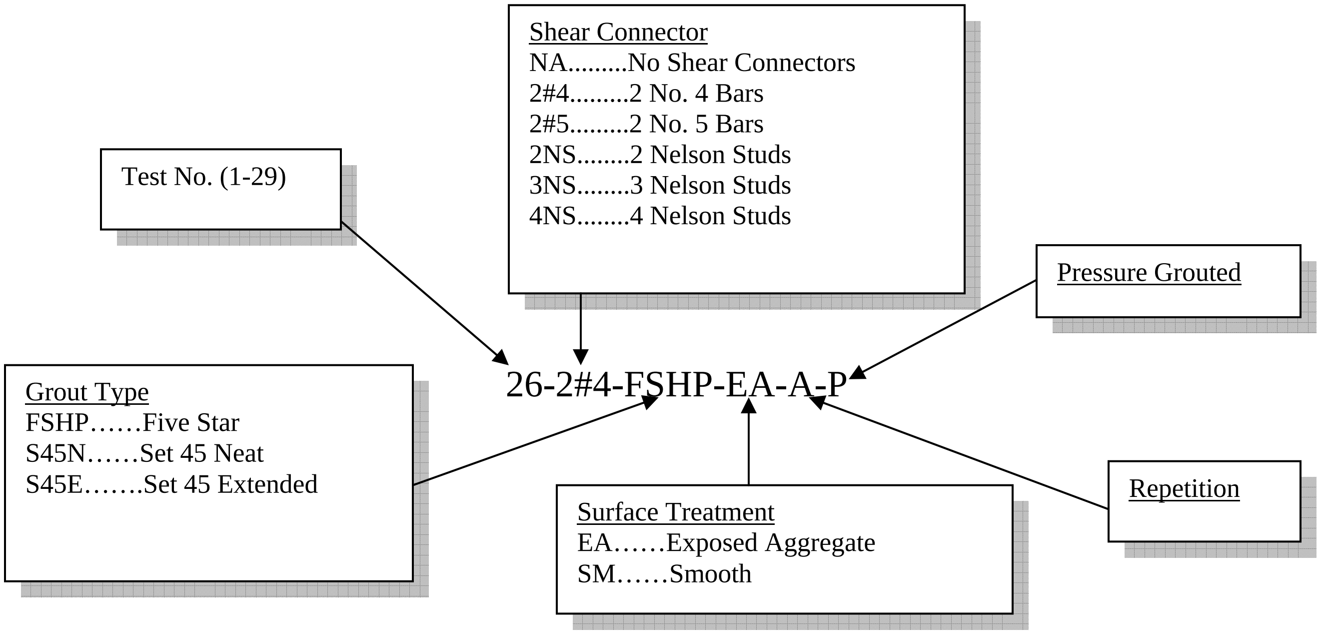


Figure 48. Specimen Grouting

Table 19 shows the combined results from all of the tests. Figure 49 is a key to decipher the test designation.



A_{cv} = Interface area

A_v = Shear connector cross sectional area

V_{peak} = Peak shear load

$V_{sustained}$ = Sustained shear load

P_n = Applied normal force

Slip = Average of both LVDT's measured slip at peak load

$\%F_y$ = Percentage of the yield stress based on measured strain

Failure plane = Haunch interface where crack first formed

f_c' concrete = Concrete compressive strength

f_c' grout = Grout compressive strength

Figure 49. Key to Test Designation in Table 19

Table 19. Push-Off Tests

Test Designation	A_{cv}, (in^2)	A_v, (in^2)	V_{peak}, (Kips)	$V_{sustained}$, (Kips)	P_n, (Kips)	Slip, in.	%Fy (60 ksi)	Failure Plane	f'_c, Grout (psi)	f'_c, Concrete (psi)	Clamping Stress at Peak Load (psi)	Post Peak Clamping Stress (psi)	Peak Shear Stress (psi)	Sustained Shear Stress (psi)	Sustained Load region (in.)
1-2#4-FSHP-EA-A	424	0.40	45.6	29.4	3.4	0.018	20	Top	4500	5900	21.7	76.8	107.5	69.3	0.15-0.30
27-2#4-FSHP-EA-B	424	0.40	39.3	34.6	5.6	0.005	4	Top	3400	4600	16.0	82.1	92.7	81.6	0.08-0.15
2-2#4-S45E-EA-A	424	0.40	40.6	27.6	4.0	0.023	21	Top	4750	5900	23.9	78.3	95.6	65.1	0.15-0.30
3-2#4-S45E-EA-B	424	0.40	28.2	28.8	3.2	0.010	18	Top	4750	5900	20.0	76.5	66.5	67.9	0.08-0.15
4-2#4-S45N-EA-A	424	0.40	45.9	25.5	6.0	0.020	20	Top	2500	6000	28.0	83.1	108.3	60.1	0.15-0.30
5-2#4-S45N-EA-B	424	0.40	47.4	36.7	5.8	0.030	20	Top	2500	6000	27.5	82.6	111.8	86.6	0.15-0.30
24-2#4-S45N-EA-C	424	0.40	52.3	33.4	6.7	0.038	20 *	Top	6200	4600	29.6	84.7	123.3	78.8	0.15-0.30
6-2#5-S45E-EA-A	424	0.62	49.1	45.3	5.6	0.039	20	Top	3600	4300	34.5	119.9	115.9	106.8	0.15-0.30
7-2#5-S45E-EA-A	424	0.62	48.7	46.1	5.1	0.072	55	Top	3600	4300	70.6	118.7	115.0	108.7	0.15-0.30
8-2#5-FSHP-EA-A	424	0.62	42.1	38.8	5.6	0.034	30	Top	3250	4300	45.3	120.0	99.2	91.5	0.08-0.15
9-2#5-FSHP-EA-B	424	0.62	50.1	37.3	6.9	0.092	31	Top	2350	4300	49.4	123.1	118.2	88.0	0.15-0.30
10-2#5-S45N-EA-A	424	0.62	66.2	53.8	3.7	0.028	36	Top	2700	4300	47.1	115.4	156.0	126.9	0.15-0.30
11-2#5-S45N-EA-B	424	0.62	42.4	43.1	4.1	0.015	68 *	Top	2700	4300	81.7	116.4	100.1	101.7	0.06-0.10
29-2#5-S45N-EA-C	424	0.62	52.0	42.9	5.8	0.036	99	Top	6200	4600	119	120	123	101	0.15-0.30
12-2#4-FSHP-SM-A	424	0.40	47.1	38.0	2.8	0.033	72	Top	3200	5000	56.2	75.4	111.1	89.6	0.15-0.30
13-2#4-FSHP-SM-B	424	0.40	50.7	40.1	2.7	0.030	57	Top	3200	5000	45.5	75.1	119.6	94.6	0.15-0.30
14-2#5-FSHP-SM-A	424	0.62	59.5	43.5	28.8	0.030	76	Top	3200	5000	149.1	174.7	140.2	102.6	0.15-0.30
16-2#5-FSHP-SM-B	424	0.62	47.1	37.8	5.3	0.038	80	Top	3500	5000	97.9	119.2	111.0	89.2	0.15-0.30
28-2#5-FSHP-SM-C	424	0.62	56.3	49.7	6.9	0.037	78 *	Top	3400	4600	99.5	123.0	132.8	117.2	0.08-0.15
15-NA-FSHP-SM-A	424	0.00	34.7	38.5	27.9	0.024		Top	3500	5000	65.8	65.8	81.7	90.8	0.15-0.30
17-NA-FSHP-SM-B	424	0.00	29.3	8.4	5.3	0.003		Top	3500	5000	12.6	12.6	69.2	19.8	0.15-0.30
18-2NS-FSHP-SM-A	424	0.88	43.7	28.0	5.0	0.116	58	Bottom	3100	5400	71.1	114.0	103.0	66.0	0.75-1.00
20-2NS-FSHP-SM-B	424	0.88	30.6	23.0	4.7	0.019	7.5	Bottom	3100	5300	18.7	113.2	72.1	54.2	0.75-1.25
19-4NS-FSHP-SM-A	424	1.77	72.4	51.7	7.1	0.129	60	Bottom	3100	5400	139.2	220.8	170.8	121.9	0.75-1.00
21-4NS-FSHP-SM-B	424	1.77	70.8	63.3	11.0	0.132	88	Bottom	2900	5300	205.6	230.1	167.0	149.3	0.25-1.00
22-3NS-FSHP-SM-A	424	1.33	57.9	41.0	6.8	0.107	56	Bottom	2900	5300	101.7	169.1	136.6	96.7	0.50-1.00
23-3NS-FSHP-SM-B	424	1.33	54.5	47.7	6.0	0.116	92	Bottom	2900	5300	155.1	167.4	128.5	112.5	0.20-0.70
25-2#4-FSHP-EA-A-P	424	0.40	42.3	36.0	4.7	0.030	100	Top	3400	4400	80.0	80.0	99.8	84.9	0.13-0.80
26-2#4-FSHP-EA-B-P	424	0.40	48.5	35.6	4.2	0.012	100	Top	3400	4400	78.8	78.8	114.4	84.0	0.10-0.30

* Percentage of yield estimated because strain gage failed prior to peak load

Tests with No Shear Connectors

Two push-off tests were done without any reinforcement crossing the interface. For the previously described investigation of cohesion, six push-off tests without reinforcement crossing the interface were performed. The only difference between the specimens in this test series was that the slab side specimens were not prepared with an exposed aggregate treatment as the previous specimens were.

The average peak shear stress of the previous six tests, which had no shear connectors, was 103 psi and the tests ranged from 79 psi to 119 psi. The average of the two tests performed with a smooth surface was 75 psi, suggesting that some additional adhesion may be obtained with an exposed aggregate slab. However, further tests are necessary to confirm this.

Tests with Shear Connectors

Two different types of shear connectors were tested in this research. The first type of connector tested was the typical reinforcing bar stirrup extending from the beam side specimen. For precast concrete beams this is the most common way of connecting the beam to the slab for composite action. Typically, the stirrups used for vertical shear are extended into the slab for horizontal shear. For these specific tests double leg stirrups of either No. 4 bars or No. 5 bars of Grade 60 steel were tested. From tensile tests the actual yield stress of the reinforcing bars was 73 ksi. The second type of connector was a headed stud. Headed studs are typically used on steel girders and have a yield stress of 49 ksi. They are generally made of mild steel and have a Young's Modulus of 29,000 ksi. A special type of welding gun is used to attach the studs in the field to the top flange of a steel girder. For the push-off tests, ¾ in. headed shear studs were used. Since this research focused on precast beams a detail allowing studs to be welded to a plate embedded in concrete was used. Figure 50 shows the plate that was embedded into the top of the beam side specimen when the concrete was placed.

Reinforcing Bar Stirrups

Various tests using two legs of No. 4 bars or using two legs of No. 5 bars were carried out. As seen in Figure 51, a bar chart of the results shows that as the size of connectors was increased the average horizontal peak shear capacity was only increased slightly. As expected the specimens containing no shear connectors had the lowest shear capacity. However, there was only a small increase in the peak shear stress of the test with No. 5 bars compared to the tests with the No. 4 bars. Figure 52 demonstrates that while the peak shear stresses are nearly the same, the tests with larger amounts of steel crossing the interface are capable of maintaining a higher post crack load.

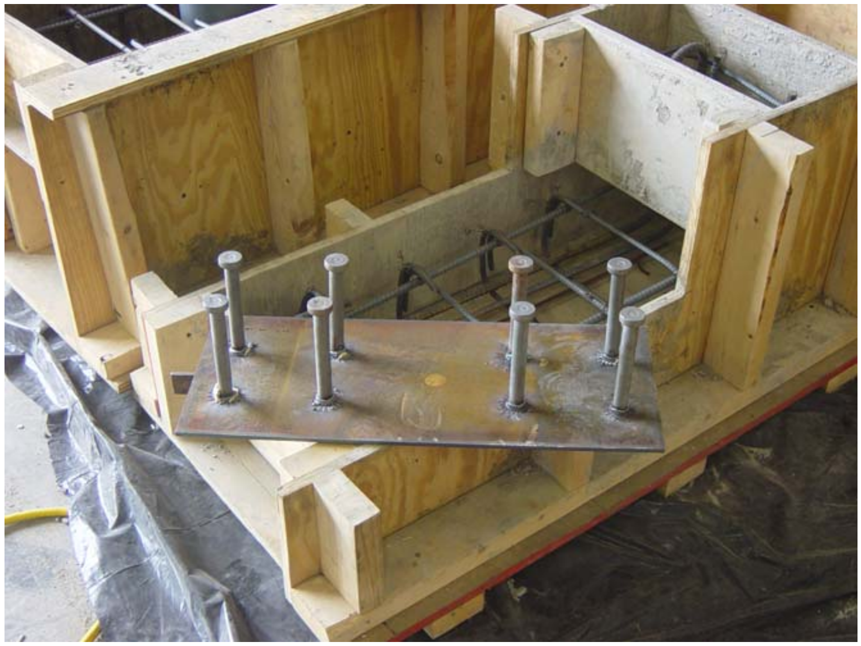


Figure 50. Plate to be embedded in top of beam side specimen

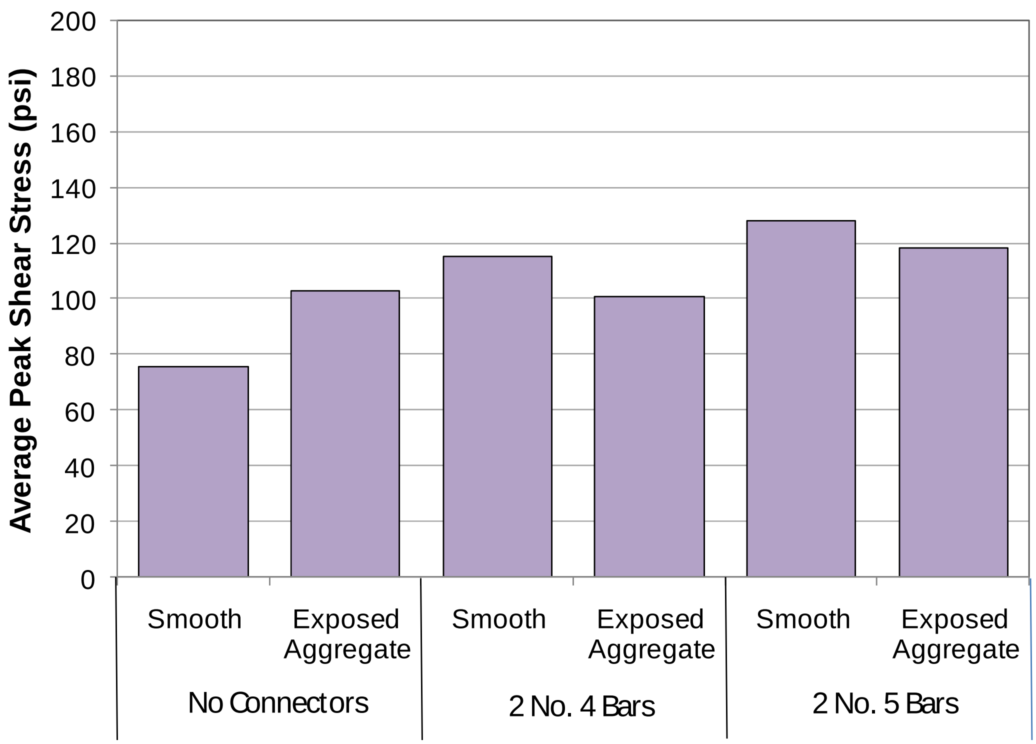


Figure 51. Average Peak Shear Stress

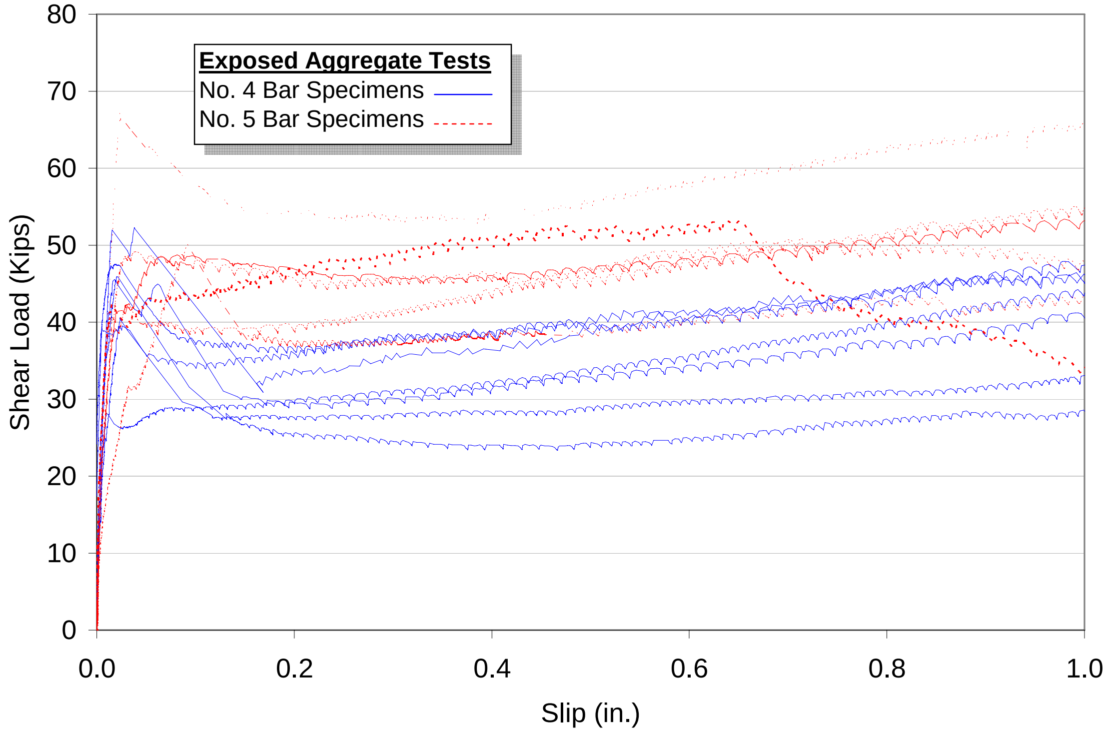


Figure 52. Load versus Slip for Exposed Aggregate Tests

Headed Shear Studs

Headed shear studs are typically used when precast slabs are supported on steel girders. Headed shear studs are advantageous since they can be welded to the girder after the panels have been placed. This eliminates problems associated with maneuvering the shear pockets over the studs as the panels are being lowered onto the girders as well as preventing fabrication errors. This series of tests consisted of specimens with groups of two, three and four ¾ in. studs. The respective amounts of steel crossing the interface are 0.88 in^2, 1.33 in^2 and 1.77 in^2. Figure 53 demonstrates that increasing the number of studs has an impact on the peak shearing stress.

This significant increase was not seen in the tests with reinforcing bar stirrups. This is likely due to the fact that there is significantly more steel crossing the interface in these tests. As the amount of steel crossing the interface is increased so is the shear resistance that the shear connectors can provide. Once the shear resistance of the shear connectors exceeds the adhesive capacity of the concrete/grout interface, the peak load can be carried by the shear connectors. For the tests with No. 4 bar and No. 5 bar stirrups the shear resistance of the stirrups was lower than the adhesive capacity and the peak load was greater than the shear resistance of the connector. This explains why the peak loads of those tests were approximately the same. Load-slip behavior is presented in Figure 54.

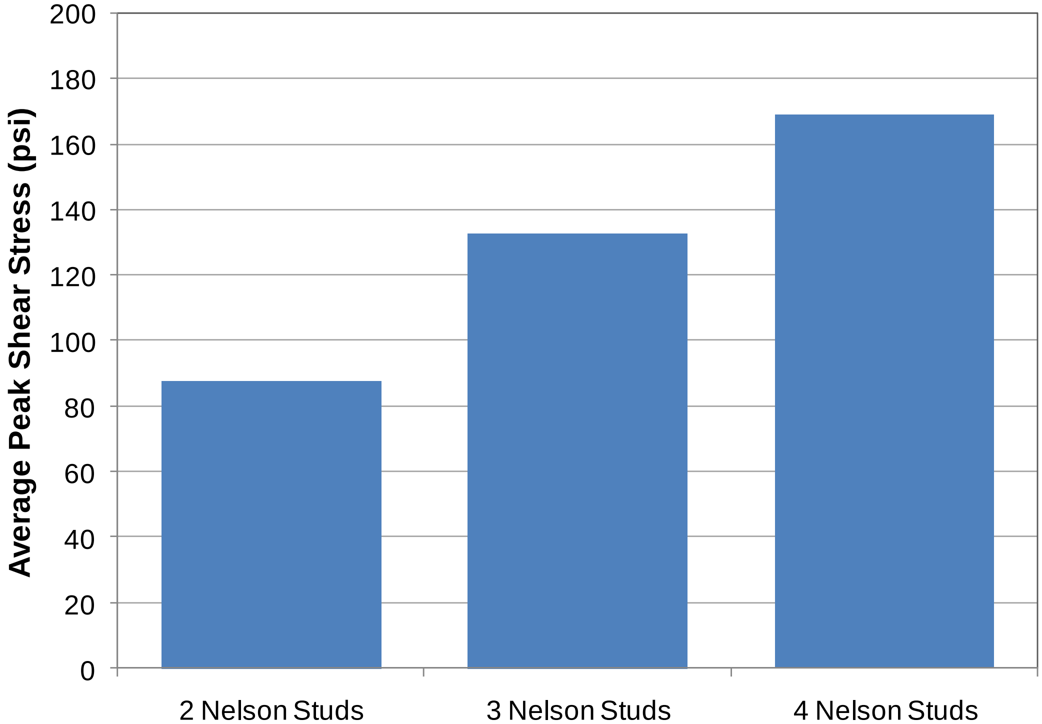


Figure 53. Average Peak Shear Stresses for Headed Shear Stud Tests.

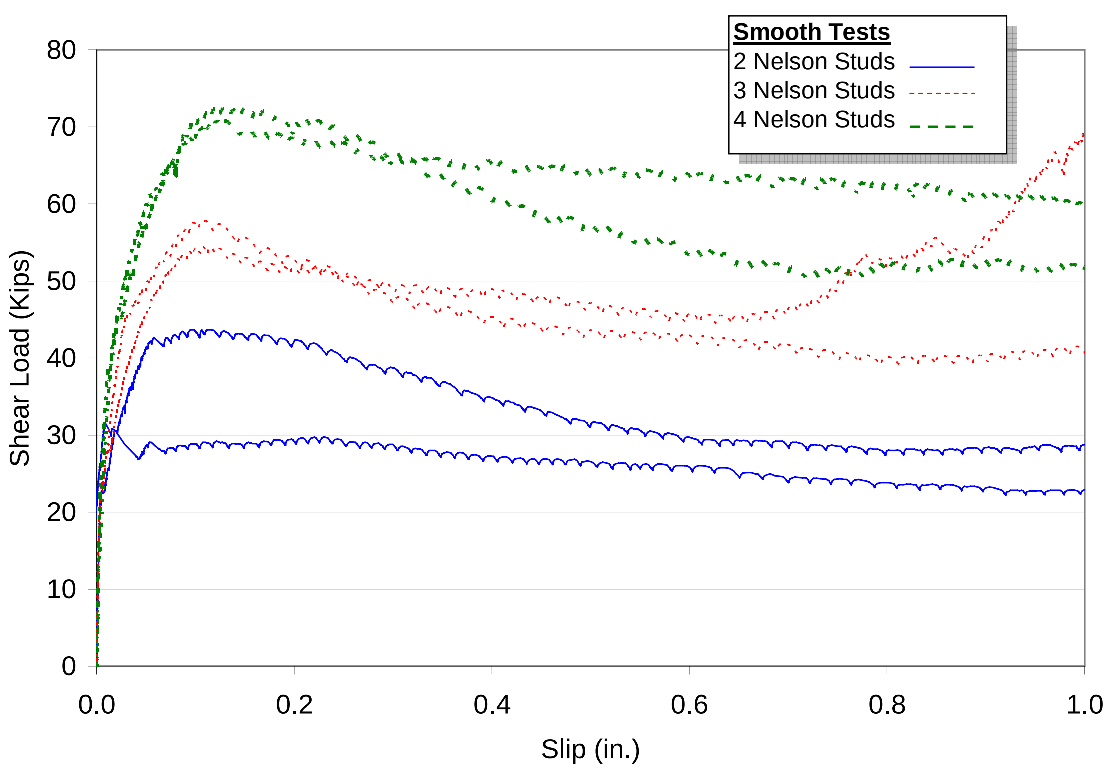


Figure 54. Load versus Slip for Headed Shear Stud Tests

Surface Treatment

To investigate an exposed aggregate surface treatment on the bottom of the slab versus a smooth finish on the bottom of the slab this parameter was varied for the double leg stirrup tests. As was seen in Figure 51 the surface treatment of the slab had little effect on the peak shear stress obtained. This is likely attributed to the casting orientation. One might expect the exposed aggregate slab to perform better. However, the casting orientation makes it easy for the exposed aggregate slab to collect pockets of air at the bottom of the slab (see Figure 48). This results both in a reduced coefficient of friction and reduced adhesion.

Hidden Pocket Detail

A trial detail of a hidden pocket was conducted. The hidden pocket was the shape of an inverted cone and had two grout vents at the top to allow air to escape. One benefit of the hidden pocket is that the riding surface of the bridge has a much cleaner and uniform appearance. As expected, the two trial tests of this detail did not show any noticeable increase or decrease in shear strength. Figure 55 shows the normal 6 in. cylindrical pocket detail strength compared with the hidden pocket detail strength.

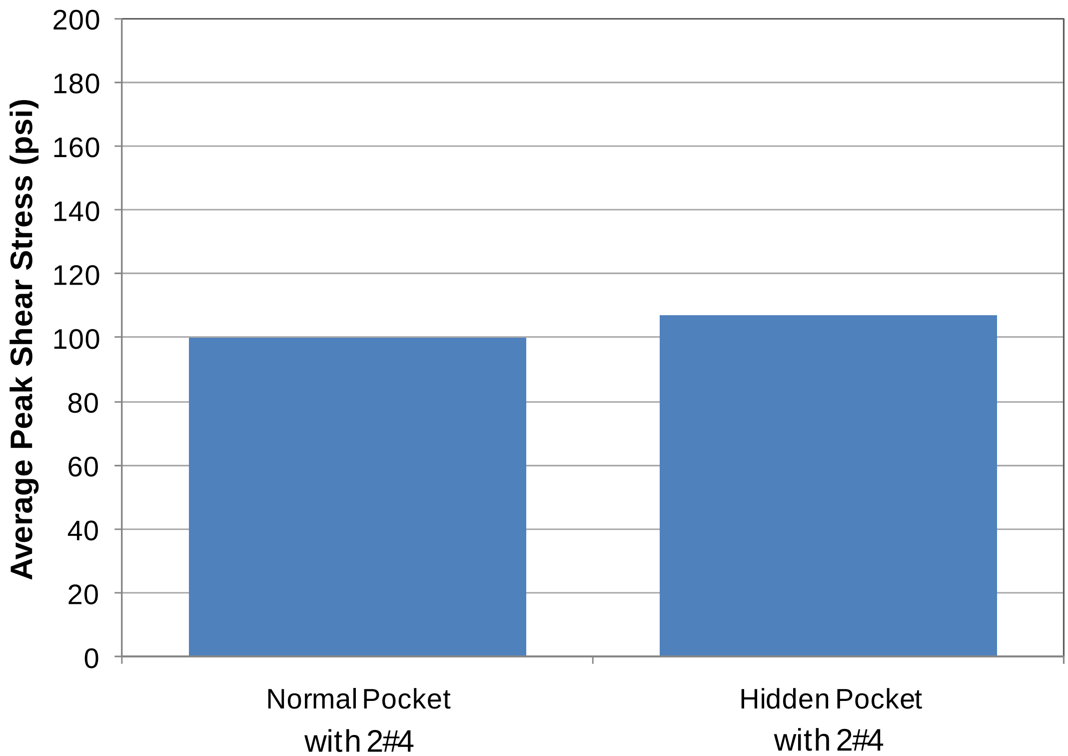


Figure 55. Normal Pocket versus Hidden Pocket Average Peak Shear Stress

Yield in Shear Connectors

Part of the theory in shear friction models is that the steel crossing the interface provides a clamping force. This clamping force is provided as a crack is opened. As the crack continues to dilate the reinforcing steel restrains the opening of that crack, providing a clamping force in addition to any normal force applied to the slab. However, there is some speculation about whether the reinforcing bars are actually fully yielded before the peak load is obtained. In most equations the stress in the reinforcing bars is taken to be the yield stress. In order to measure the axial stress in the reinforcing bars, strain gages were applied to the shear connectors at the level of the haunch. Unfortunately, strain gages are extremely sensitive and are easily damaged. Several of the strain gages were damaged by the grout and concrete around them before the peak load was reached. Figure 56 shows the average percent of yield for the various connector arrangements. It appears that as the cross-sectional area of the connectors increases, the connectors are closer to yield.

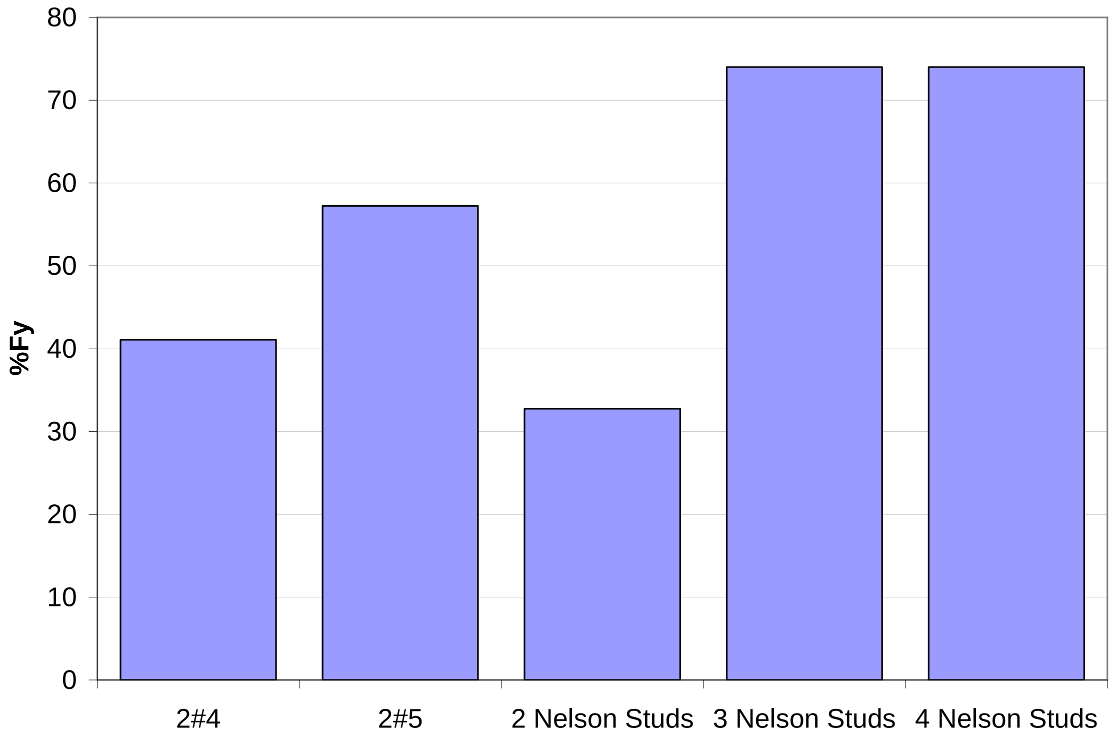


Figure 56. Percent of Yield Stress in Shear Connectors at Peak Load

In general if the horizontal shear resistance of the shear connectors is greater than the shear resistance from adhesion then the reinforcement will be yielded at the peak load. If the connectors crossing the interface have less resistance than the resistance provided by adhesion the yielding of the connectors occurs sometime after the peak load. This happens after a slip in the range of 0.15 in. to 0.30 in. has occurred.

Coefficient of Friction

If the clamping stress versus shear stress is plotted for the sustainable load which occurs just past peak, a coefficient of friction can be determined. The coefficient of friction can be taken as the slope of the line passing through zero. This is not a true coefficient of friction, as in the coulomb friction equation. Since there are shear connectors present, this coefficient of friction also accounts for the shear resistance provided by the shear connectors. Since these are post-peak loads, the stress in the steel is taken to be at yield. From tension tests, the actual average yield stress of the reinforcing bar stirrups used in this research was 73 ksi. Figure 57 shows the coefficient of friction for the reinforcing bars stirrup tests as $\mu = 0.9$ and Figure 58 shows the coefficient of friction for the headed shear stud tests as $\mu = 0.6$. As expected the tests with headed shear studs exhibited a lower friction coefficient. These tests cracked at the interface between the beam and haunch rather than on the slab side. This was expected since this surface consisted of grout against the steel plate embedded in the concrete, a much smoother surface with less adhesion.

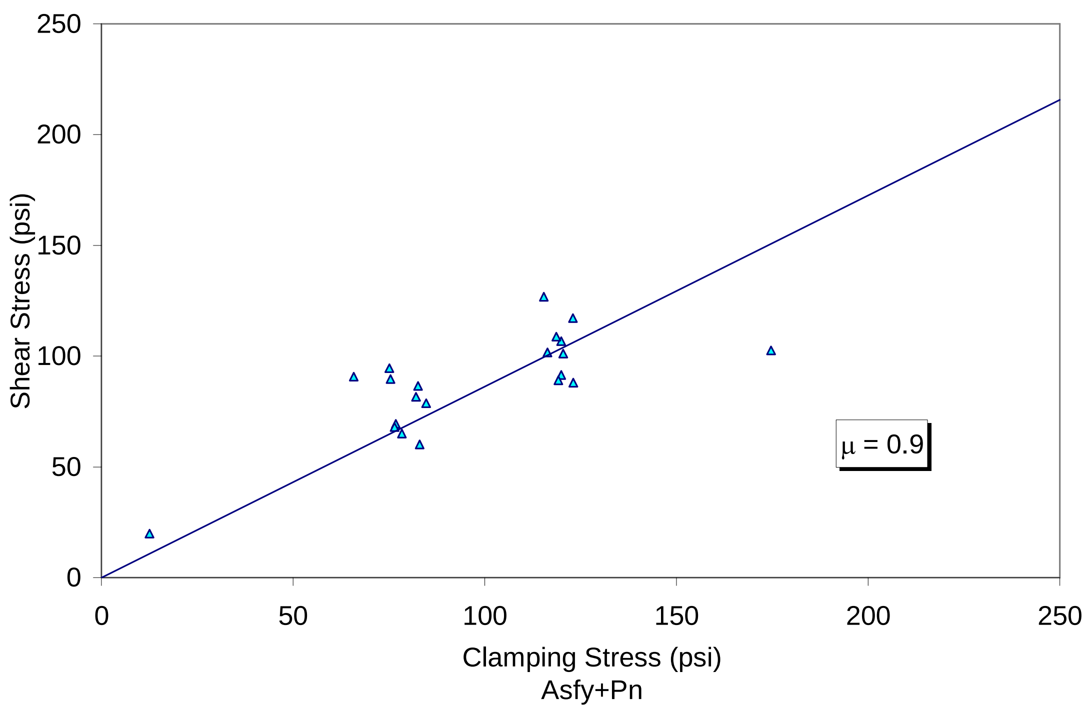


Figure 57. Reinforcing Bar Stirrups and No Connectors at Sustained Load

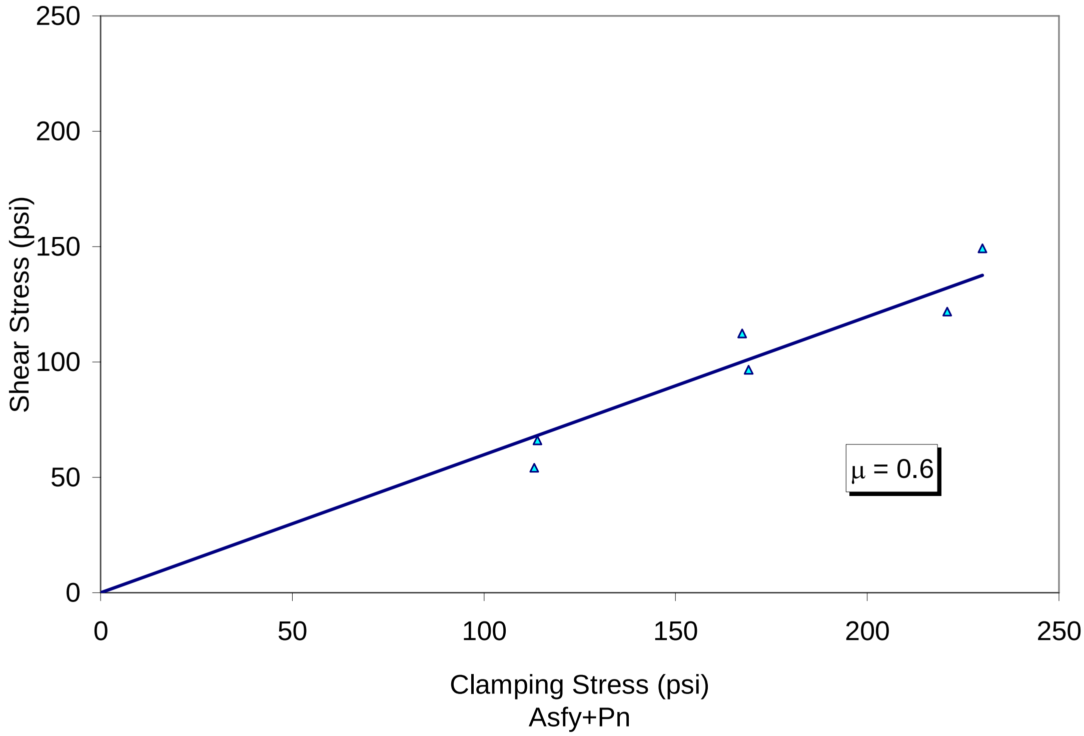


Figure 58. Headed Shear Stud at Sustained Load

Comparison with Current Code Equations

Figure 59 is a plot of the peak shearing stresses versus clamping stress. Overlaid on this plot are the AASHTO LRFD (2004) equations. The different equations are for concrete placed against hardened concrete with a roughened surface, concrete placed against hardened concrete without a roughened surface and concrete placed against a steel surface.

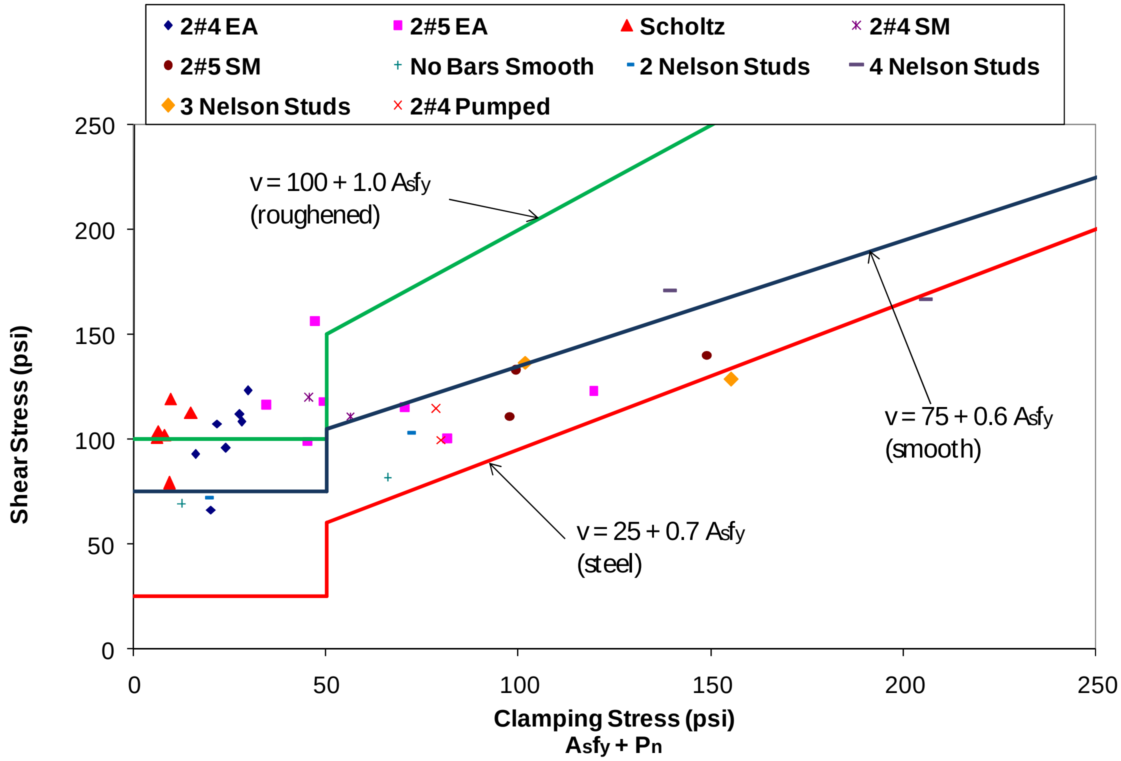


Figure 59. Peak Shear Stress vs. Clamping Stress

Based on the results of this research, the current shear friction design philosophy requires revision. Currently the AASHTO LRFD manual allows the designer to take the horizontal shear strength as the combination of the chemical adhesion at the interface plus coulomb friction with the clamping force being provided by steel crossing the interface plus any normal force provided by the deck and appurtenances. In actuality, resistance provided by friction does not occur until a crack is formed. A crack is formed when the adhesion bond is broken. The proposed modification to the AASHTO equation would be as follows if the two components are separated. This is consistent with the results seen as the amount of steel is increased.

$$v_n = \max \left| \begin{array}{c} cA_{cv} \\ \mu(A_s f_y + P_n) \end{array} \right.$$

where
c = cohesion = 75 psi
A_{cv} = Interface area
μ = 0.9 for a grout on concrete interface
    0.6 for a grout on steel interface
A_s = Area of shear connector crossing interface
f_y = Connector yield stress
P_n = Additional normal force

The coefficient of friction in the shear strength equation also accounts for the contribution of shear resistance provided by dowel action of the shear connectors. When the shear portion of the equation controls, it is acceptable to use the yield stress, since in these cases the peak load is occurring near the point when the reinforcement yields. It is recommended that a minimum area of steel criteria be established. However, based on this research there is insufficient data to establish a minimum area of steel. Figure 60 shows the proposed equation plotted against the results from this research. As one would expect the peak load results plot just above the adhesion or friction line and the post peak results plot along the friction line as seen in Figure 61.

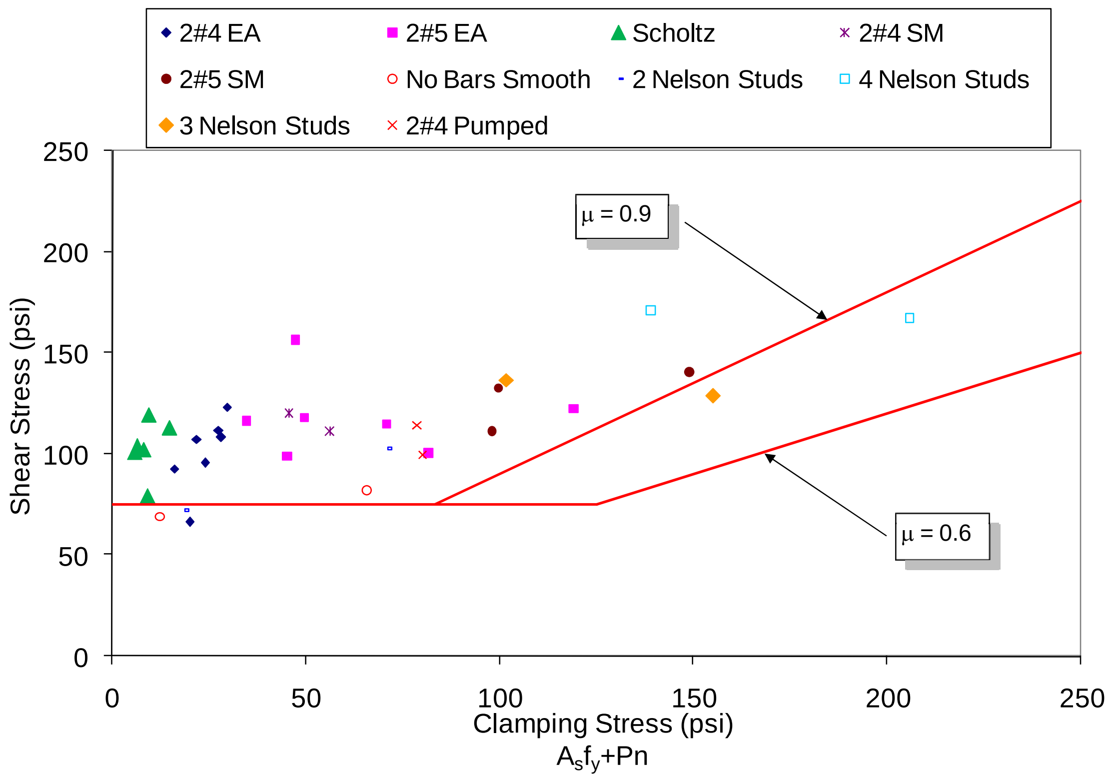


Figure 60. Peak Shear Stress Results with Proposed Equations

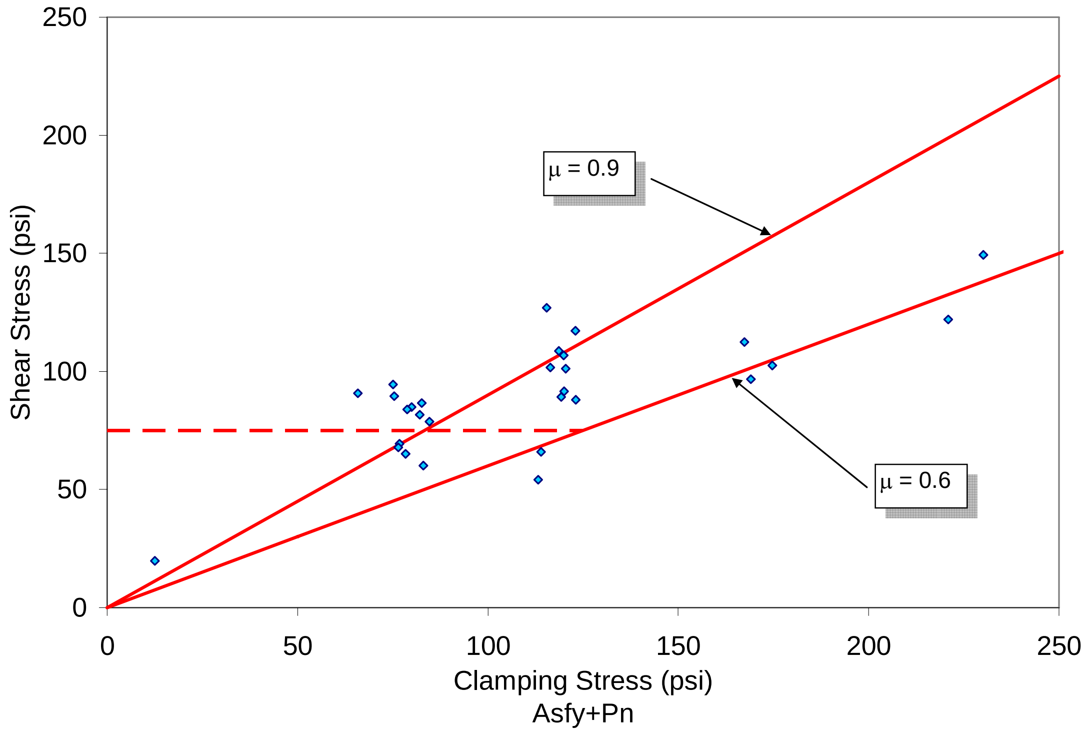


Figure 61. Post Peak Results with Proposed Equations

CONCLUSIONS

Conclusions from Grout Research

A series of ASTM standard tests and representative deck panel system tests were performed on four candidate grouts with and without a pea gravel aggregate extension to determine suitable performance criteria for a precast concrete bridge deck panel system. These tests investigated essential grout properties including compressive strength, tensile strength, shrinkage, workability, flow, and bond strength. The objective was to correlate grout performance between the ASTM and representative tests so that a design specification could be developed and used in the selection of mortars for a precast concrete bridge deck panel system.

Compressive Strength

It was evident that a very high early compressive strength can hinder the ability of a mortar to flow. This is unacceptable in all cases, because it is of utmost importance that the haunch and shear pockets are completely filled with grout in order to ensure the best connection between the beam and precast deck panel. From a construction standpoint, it is very unlikely that a transportation authority would desire to open a bridge to traffic only one hour after the start of the grout pour, although it could be more feasible in a deck replacement situation. In addition to the amount of time it takes to pour the grout throughout the length of the bridge over multiple beam lines, there are many other tasks to accomplish before a bridge could be opened.

These tasks include the placement of barriers, removal of temporary traffic control devices, general cleanup, and dispersion of personnel. In most cases, a high one hour strength would not be critical, and would most likely be detrimental. Strength gain in the second hour would be more appropriate if the panel system is being utilized to rehabilitate a deteriorated deck and partial or night-time bridge closures are employed. A high two hour compressive strength would ensure that the bridge could be opened to traffic as soon as possible. Therefore, it is recommended that the mortar gain very little strength within the first hour, and gain a minimum two hour compressive strength of 2000 psi in accordance to ASTM C 109. These early strength parameters should ultimately be determined by the engineer-of-record for each specific use of the deck panel system. A high two- hour strength may not be critical if the panel system is used in conjunction with new bridge construction or full lane closures. A recommended minimum one day compressive strength is 4000 psi and a recommended minimum seven day compressive strength is 5000 psi. This high compressive strength is desirable so that the grout is consistent with the precast concrete deck panels. Deck panel compressive strength usually ranges from 4000 psi to 6000 psi.

Since not all manufacturers will specify compressive strengths for their products at these exact time intervals, alternate criteria need to be established as well. Any alternate criteria used in specifications must be stricter than the original criteria so that manufacturers are not tempted to omit information in order to meet standards. In lieu of two-hour compressive strength, a recommended minimum three-hour compressive strength is 3000 psi. In lieu of seven-day compressive strength, a recommended minimum 28-day compressive strength is 6000 psi.

Tensile Strength

To ensure that a grout does not exhibit diagonal tension cracking in haunch conditions, a recommended splitting tensile strength at one day is 200 psi and at seven days is 400 psi in accordance to ASTM C 496. A recommended alternate criteria is 600 psi at 28 days in lieu of the seven-day criteria. It may be difficult to ensure that diagonal tension cracking does not occur in the mortar at negative moment regions of a continuous beam. A detailed analysis of the stresses in the haunch at these locations should be carried out for each specific bridge configuration. It is also possible that a manufacturer may not specify a splitting tensile strength. In this case, criteria should be established based on a relationship between compressive strength and tensile strength. A common assumption for concrete is that tensile strength is approximately equal to 1/10 of the compressive strength. For each of the candidate mortars investigated in this research, the tensile strength ranged from 1/8 to 1/14 of the compressive strength. In order for these alternate criteria to be more conservative than the original criteria, 1/15 was selected as a multiplier to estimate the splitting tensile strength from the compressive strength.

Shrinkage

Two of the four neat grouts and two of the four extended grouts performed well in the shear pocket tests, with no cracks forming or water seepage through the interface. Unfortunately, there was no correlation found between the amount of differential shrinkage and the development of cracks at the interfaces. Still, it is prudent to limit grout shrinkage to avoid, as much as possible, the tensile stresses that develop from the restraint of shrinkage. Therefore, a recommended maximum 28-day shrinkage is 0.04% (400 microstrain) in accordance to ASTM C 157 or ASTM C 596. This maximum is recommended for both neat grouts (1 in. square cross section prisms) and extended grouts (3 in. square cross section prisms).

Flow and Workability

It has been recommended that the grout gain very little strength in the first hour to ensure that it does not set too quickly and adversely affect its flow. Work time and initial set time should not be less than 15 minutes and 30 minutes, respectively, although longer times are preferred. Additionally, it is recommended that a grout be tested on site, immediately after mixing, in accordance with ASTM C 1437 (modified). It is recommended that the grout achieve a self-weight average spread of 7 in. and a 9 in. average spread after ten drops on a standard drop table specified by ASTM C 230 (modified from 25 drops).

Bond Strength

The slant shear cylinder tests (ASTM 882) may not be representative of horizontal shear strength as they did not accurately predict the mortars' performance in push-off tests. A definite correlation was not identified between the two types of tests. However, a grout should be able to provide an adhesion of at least 100 psi (0.1 ksi) in order to meet the assumed cohesion factor used in the AASHTO LRFD Specifications. Further research should be carried out in order to correlate horizontal shear strength in haunch conditions with slant shear cylinder tests or another type of bond strength test. This would allow for performance criteria to be established in order to qualify candidate grouts for use in a precast deck panel system based on bond strength.

Adhesion

The adhesions tests showed that a saturated surface dry condition significantly improves the adhesion of the grouts to previously cast concrete. However, sand blasting was not shown to have a consistently beneficial effect. Since precast deck panels have a very large area of precast concrete that will be in contact with cast-in-place grout, the elimination of sandblasting could significantly decrease costs and speed up construction.

No strong correlation was seen between the grouts that developed leaks in the pocket mock-up tests and the adhesion tests.

Aggregate Extension and Water Content

The use of an aggregate extension with the candidate grouts in this research did not significantly hinder each grout's performance. Therefore, an aggregate extension is suitable for grouts used in a precast deck panel system. Advantages to using an aggregate extension include increasing the grout's yield volume, lengthening the grout's work time, achieving a consistency similar to that of concrete, and reducing costs. It is recommended that the aggregate be 3/8 in. pea gravel and that the extension be no greater than 50% by weight. This research has shown that a greater extension hinders the grout's workability and flow capability. A 50% or less extension can slow the set of the grout and extend its work time, which is a valuable feature for a precast deck panel pour. It is recommended that the specified maximum water content be used for each grout. This use of additional water aids the grout's workability and flow without significantly compromising strength gain. The water content should never exceed the maximum content specified for each grout, and water should never be added once pouring has commenced in an attempt to increase its workability.

Properties Not Investigated in This Research

Nottingham (1996) recommended criteria for some durability-based mortar properties that were not investigated in this research (see Table 1). These recommendations were applied to the proposed performance specification in the Appendix.

Additional Recommendations from Grout Tests

- In the slant shear tests, sand blasting did not significantly increase the bonding capabilities of a concrete surface which had already been raked to an amplitude of ¼ in. It may be unnecessary to perform this time-consuming and expensive task in this situation.

- A ¼ in. raked surface preparation is suitable for the top flange of a conventional concrete beam. Surface preparations to provide adequate bond between the grout and self-consolidating concrete should be investigated. A smooth finish may be adequate based on results showing the bond to be very similar (see Figure 51).

- Grouts should be poured continuously along beam lines starting from the center of each span and working towards the supports. This takes advantage of the beams' camber so that the mortar is flowing in a downhill manner. If the bridge is inclined, the grout should be poured downhill.

- Based on their performance throughout this research, Five Star® Highway Patch (3) and Set® 45 Hot Weather (4) are suitable for use in a precast concrete bridge deck panel system. Five Star® Highway Patch extended (7) and Set® 45 Hot Weather extended (8) also performed very well, but were hindered in constructability considerations due to their high aggregate extensions. If their extensions were reduced to 50% by weight, it is expected that both extended products (7 & 8) would be suitable for use in a precast deck panel system. Although Five Star® Highway Patch (3 & 7) and Set® 45 Hot Weather (4 & 8) are more expensive than ThoRoc® 10-60 and SikaQuick® 2500, transportation authorities should realize that using grouts that are suitable for this application is critical to ensuring a properly functioning deck system, even at higher initial construction costs. Using less-expensive grouts that are inappropriate for use in a precast deck panel system could be detrimental to the structural integrity of the bridge and could force a very costly rehabilitation in the future.

Conclusions from Horizontal Shear Strength Studies

The results do not indicate any significant increase in strength when the bottom of the slab is prepared with an exposed aggregate surface. When the headed shear stud system is used an exposed aggregate surface treatment is not required since the failure plane is then at the beam to haunch interface.

The headed shear stud system which utilized welded stud connectors on a plate that was embedded in the top flange of the beam had successful results. The specimens performed very similarly to the test specimens that utilized the typical reinforcement bar stirrups. Headed shear studs do have a lower yield stress though, so an increased number of studs may be required.

The inverted cone hidden pocket system also performed comparably with the normal pocket detail. The disadvantage to the system is that it can be cumbersome to form and remove the forms for the pocket. An inverted cone such as the one used in this research is likely not necessary. A simple cylinder or truncated cone with the wider side down would be easier to form and likely produce the same results.

The tests performed in this research indicated three different types of behavior based on the amount of steel crossing the interface. If the amount of steel crossing the interface had shear resistances lower than adhesion a sudden slip occurred when the crack between the interfaces formed. When the amount of resistance provided by the connector was roughly equal to the adhesion a sudden slip was still noted but the sustained load was approximately equal to the peak load. When the amount of resistance from the shear connectors was much greater than the adhesion as the crack formed, the steel began to progressively take the load until the steel yielded. No sudden slips were noted for these tests. For those tests with low amounts of steel the stress in the shear connector was not near yield at the peak stress. For those with higher amounts of steel the stress in the reinforcing bars was closer to the yield stress. Beyond the peak load the yielding of the connectors was obtained generally within a slip of 0.15 in. to 0.30 in.

For low clamping stresses, the AASHTO equations were mostly successful at predicting the horizontal shear strengths. Values for adhesion based on a non-roughened surface provided the closest representation of the data.

From the experiences of this research it is important to make sure that the quality of the formwork used for grouting operations is good. In order to have good flow with the grout it is recommended that the maximum amount of water be used. With this high degree of flow it is imperative that the formwork be tight against the concrete and small crevices filled with a weather stripping material or caulk. Care must also be taken that enough time is available to finish grouting operations. Grouts have very fast set times. It is important to determine that the grout can be batched and placed before the grout begins to set, as the grout can set in a matter of minutes. Both the Set 45® Hot Weather Grout and the Five Star® Highway Patch grouts performed well with good flow characteristics and compressive strength. The Set 45® Hot Weather extended with pea gravel also performed well and it is recommended that all the manufacturer’s instructions be carefully followed when batching grout.

RECOMMENDATIONS

Grout Specification

1. *VDOT's Structure & Bridge Division should adopt a grout specification to ensure that the grout used in precast deck panel projects will perform well during construction and over the life span of the deck.* A recommendation for this specification is presented as Appendix A. Durability recommendations are adopted from Nottingham (1996).

Horizontal Shear Strength

2. *VDOT's Structure & Bridge Division should design horizontal shear connectors for precast deck panels on precast I-beams using the AASHTO LRFD equation for smooth surfaces when extended reinforcing bars are used as the shear connector.*

3. *If the embedded plate and welded shear stud detail is used, VDOT's Structure & Bridge Division should design the connections for strength using the AASHTO LRFD equation for horizontal shear strength on steel.* However, the studs also need to be checked for fatigue in accordance with chapter 5 of LRFD.

Construction Recommendations

4. *VDOT's Structure & Bridge Division should specify a smooth bottom surface on precast deck panels along girder lines.* Based on this research, no significant increases in strength were found by exposing the aggregate on the bottom slab surface. Based on test results, an exposed aggregate surface on the bottom of the slab does not provide a sufficient increase in horizontal shear resistance to justify the additional cost of exposing the aggregate.

COSTS AND BENEFITS ASSESSMENT

The initial construction cost of a bridge deck comprising precast deck panels may be higher than a cast-in-place deck, but tremendous benefit can be found in the greatly reduced construction time and greatly enhanced durability of the deck. Sources have quoted the initial cost of a bridge deck replacement with full-depth precast deck panels at between $50 and $70 per square foot, compared to cast-in-place (CIP) deck replacement costs between $28 and $40 per square foot (HSMM 2007, MoDOT 2005, Balakrishnan 2006). However, the same sources have also noted the greatly reduced construction time for full-depth precast decks compared to CIP decks. HSMM predicted 20% to 30% reductions in detour time with greater flexibility in staged construction options. This allows for closing lanes during low traffic times (nights and weekends), and reducing or eliminating lane closures during heavy traffic hours.

Calculating road user costs associated with construction delays is extremely complex, involving vehicle operating costs, user delay costs, and accident/crash costs, along with information about original number of lanes and average daily traffic, number of lanes closed due to construction, original travel speed and others. A single number to examine is the cost of a fatal accident. This cost has been quoted as between $1 million and $3.4 million depending on the source (Rister and Graves 2002). If the reduced detour time, and more flexible detour staging afforded by precast bridge deck panels prevents just one work zone fatality, the cost of 40,000 square feet of more expensive bridge deck is well justified [$1 million/($25/sq. ft. premium)].

In conclusion, it is recognized that the initial costs for full-depth precast bridge decks are greater than for cast-in-place decks, but the reduced construction time and reduction in associated road user costs can easily offset the higher construction cost.

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APPENDIX A

PROPOSED PERFORMANCE SPECIFICATIONFOR GROUTS USED IN FULL-DEPTH PRECAST CONCRETE BRIDGE DECK PANEL SYSTEMS

This performance specification is intended to qualify mortar or grout products for use in a precast concrete bridge deck panel system. Section 1 through Section 7 are intended to evaluate a product based on accompanying technical data, while Section 9 is intended to evaluate a product on site at the time of the pour. Section 8 provides mixing procedures.

1. Product Composition

1.1 Neat Grouts: The product shall be composed of all fine particles and have a consistency of a powder. Water shall be the only additive required.

1.2 Extended Grouts: A 3/8 in. pea gravel aggregate extension may be used in conjunction with a neat grout. The extension shall not exceed 50% by weight. The aggregate shall comply with the current state-of-art specification for pea gravels.

1.3 Neat and extended grouts must comply with the specifications set forth in Section 2 through Section 9.

2. Compressive Strength

2.1 The product shall meet the following time-based criteria for compressive strength based on ASTM C 109:

- 1 hour: No strength
- 2 hour: Determined by engineer-of-record based on construction procedure.
- 1 day: Minimum 4000 psi
- 7 day: Minimum 5000 psi

2.2 If a 7 day compressive strength is not available for a product, the following criteria shall be used:

- 28 day: Minimum 6000 psi

3. Splitting Tensile Strength

3.1 The product shall meet the following time-based criteria for splitting tensile strength based on ASTM C 496:

- 1 day: Minimum 200 psi
- 7 day: Minimum 400 psi

3.2 If a 7 day splitting tensile strength is not available for a product, the following criteria shall be used:

- 28 day: Minimum 600 psi

3.3 If no splitting tensile strength information is available for a product, the following criteria shall be used:

- 1 day compressive strength divided by 15 must be greater than 300 psi
- 7 day compressive strength divided by 15 must be greater than 400 psi
- 28 day compressive strength divided by 15 must be greater than 500 psi (in lieu of 7 day strength)

4. Shrinkage

4.1 The product shall meet the following criteria for shrinkage based on either ASTM C 157 or ASTM C 596. Neat grouts shall be evaluated with 1 in. square cross section prisms and extended grouts shall be evaluated with 3 in. square cross section prisms. The criteria shall remain the same regardless of test prism size.

- 28 day: Maximum 0.04% (400 microstrain)

5. Sulfate Resistance

5.1 The product shall meet the following criteria for sulfate resistance based on ASTM C 1012. Neat grouts shall be evaluated with 1 in. square cross section prisms and extended grouts shall be evaluated with 3 in. square cross section prisms. The criteria shall remain the same regardless of test prism size.

- 28 week: 0.10% (1000 microstrain)

6. Freeze-Thaw Resistance

6.1 The product shall meet the following criteria for freeze-thaw resistance based on ASTM C 666, Procedure A:

- 300 Cycles: Minimum 80% Durability Factor

7. Scaling Resistance

7.1 The product shall meet the following criteria for scaling resistance based on ASTM C 672:

- 25 Cycles: 0 Scaling Rating (no scaling)

8. Mixing Procedure

8.1 If an aggregate extension is used, the aggregate shall be added to the initial water content before any powder is added.

8.2 The powder shall be added to the specified minimum water content. An additional water amount shall be supplied after approximately 80% of the product has been added to the initial water. This additional water amount may be specified by the manufacturer or may be taken as the difference between the specified maximum water content and the specified minimum water content. The specified maximum water content for a specific product shall not be exceeded. No water shall be added to the product once pouring has commenced.

9. Flow

9.1 The product shall be tested according to 9.2 on site, after mixing and immediately before pouring the product.

9.2 The product shall be tested on a standard flow table specified by ASTM C 230. The testing procedure shall follow ASTM C 1437 with the following modifications:

- The average diameter of the product shall be measured after the mold is lifted to determine the product's flow under its own self weight.
- The table shall then be dropped 10 times in 15 seconds.
- The average diameter of the product shall be measured after the 10 drops
- If either the self weight or 10 drops causes the product's diameter to exceed the diameter of the table, then that measurement shall be recorded as the diameter of the table.

9.3 The product shall meet the following criteria for flow based on the procedure in 9.2:

- Minimum average diameter from self weight flow: 7 in.
- Minimum average diameter after 10 drops: 9 in.