RECLAMATION

Managing Water in the West

Report No. MERL-2013-63

Moisture Content Requirements for Repair, Part 1: Concrete Repair Testing

Science and Technology Project ID: 6629

Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Prepared by: Benoît Bissonnette, Alexander M. Vaysburd, Kurt F. von Fay — Date 12/1/14
Materials Engineering and Research Laboratory 86-68180

Checked by: Kurt F. von Fay — Date 12/1/14
Civil Engineer, Materials Engineering and Research Laboratory 86-68180

Peer Reviewed by: Matthew J. Klein, PhD — Date 12/3/2014
Civil Engineer, Materials Engineering and Research Laboratory 86-68180

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Acronyms, Abbreviations, and Definitions

° C degree Celcius

° F degree Fahrenheit

% percent

ACI American Concrete Institute

ASTM American Society for Testing and Materials

COV (%) coefficient of variation, percent

$f_{c\ x\text{-}d}$ compressive strength at x days' age

h hour

in inch

kg/m^3 kilogram per cubic meter

L/m^3 liters per cubic meter

lb/ft^3 pound per cubic foot

lb/yd^3 pound per cubic yard

MERL Bureau of Reclamation's Materials Engineering and Research Laboratory

mm millimeters

MPa megapascal

oz/yd^3 ounces per cubic yard

mL/m^3 milliliters per cubic meter

psi pounds per square inch

RH relative humidity

RILEM Réunion Internationale des Laboratoires et Experts des Matériaux, systèmes de construction et ouvrages (International Union of Laboratories and Experts in Construction Materials, Systems and Structures)

SSD saturated surface sry

Std. Deviation standard deviation

w/c water to cement or cementitious materials ratio

Background

Repair and strengthening of existing concrete structures is among the biggest challenges the industrial countries will have to face in the years to come. Moreover, the number of aged concrete structures keeps growing and therefore the needs for effective repair, retrofitting and strengthening are increasing. Among different approaches being considered for the rehabilitation needs, concrete surface repairs and bonded overlays are often the most used economical solutions.

Despite extensive use of surface repairs and overlays in rehabilitation of existing concrete structures over the last 25 years, failures are still often observed in practice. Irrespective of the methods selected, a fundamental requirement for successful repair is the achievement of strong and durable bond between the repair and the existing concrete substrate. Monolithic isotropic action of the repaired structure is a prerequisite for withstanding the imposed loads and resisting the various concrete deterioration processes. The strength and integrity of the bond depend upon the properties and characteristics of the repair material, but also to a significant extent upon preparation and conditioning of the surface to be repaired.

Concrete repair and rehabilitation commonly involve removing unsound concrete before the placement of a repair material. Regardless of the quality of repair or overlay material used and application method employed, the care with which the concrete substrate is prepared and conditioned prior to application of repair material will often determine whether a repair project will be a success or a failure. The surface preparation for repair affects the strength and durability of the bond between the “old” and “new”, between the existing concrete and repair material.

Surface preparation and moisture conditioning of the concrete substrate are generally considered to be two of the most influential steps in concrete repair works. A poorly prepared substrate will always be the weak link in a composite repair system, no matter how good the existing concrete and the repair material might be.

Concrete repair and bonded overlay are composite material systems. In such composites, the bond between the individual components is most critical for overall viability. The durability of the bond in repair or overlay systems can be defined as the lasting interfacial integrity of existing concrete and repair material. Of course, it is realized that high initial bond (short term) strength does not guarantee durability, but low initial bond may be a cause for debonding in service.

Therefore, assuming all properties of the substrate and repair material are adequate, any improvement of the bond will result in improved properties and long-term performance of the entire composite system.

Development and magnitude of interface bond strength and durability greatly depend on concrete substrate surface preparation and moisture condition prior to repair / overlay application. For this very critical parameter, quite limited reliable guidance is available for the designer and practitioner. Design specifications and guidelines are commonly very primitive and usually restricted to substrate concrete removal and cleaning methods and mechanical bond strength at 28 days – a short-term property. The moisture condition of the substrate, which is important for bond development, and therefore proves to be a crucial indicator of repair / overlay durability, are not addressed at all, or addressed without any due consideration to the given substrate characteristics.

The influence of surface moisture on the bond between old concrete and repair is an issue of significant importance. Saturated surface dry (SSD) conditioning of the substrate prior to application of cementitious repair materials is usually recommended and used, which underlies the "*layman's*" instinctive solution to avoid problems rather than achieve the most effective bond. But after all, there is no clear physical meaning defining the SSD condition, neither qualitatively nor quantitatively. There exists no strict definition of what actually is SSD: saturation to what degree, to what depth, how to measure it, etc.

The need for reliable practical recommendations regarding surface conditioning of concrete substrate prior to repair and overlay has been recognized by researchers and practitioners (1), (2), (3). It is crucial to understand that the *in-situ* performance of repairs and overlays is not only dependent on the material components and how the composite system, as a whole, respond to loads and environmental influences, but also to a large degree on the processes involved in the formation of the interface between the existing concrete and the repair material. In particular, the moisture condition of the substrate surface influences mass transport between the two phases forming the repair composite system. Literature survey results allow for the conclusion that each given combination of existing concrete substrate and repair material has specific moisture conditions at the time of placement.

Mechanical adhesion in concrete members repaired or overlaid with cement-based materials relies on the hardening of the semi-liquid mixture inside the open cavities and asperities (open pores) of the substrate surface and the physical anchorage resulting from it. Capillary absorption plays an important role in the anchorage effect as it draws the cement paste from the material mixture into the substrate, which is strongly influenced by surface moisture condition.

The substrate moisture condition may have a significant influence on bond strength and durability. A very dry "thirsty" concrete surface tends to "suck" water from the repair material, which may have negative and positive effects on bond depending upon the magnitude of "suction" and amount of available moisture in repair material. A surface, which is too wet, may dilute the repair material at the interface. To improve the performance of composite concrete repair systems, and the bond at the interface in particular, it is essential to gain a better understanding of the different transport processes between the semi-liquid repair material and solid concrete substrate.

The moisture transport mechanisms are controlled by two underlying phenomena: absorption and adsorption. Absorption describes processes, such as capillary suction and osmosis, that may draw water into concrete substrate. Adsorption processes, which result from a range of physical surface properties and phenomena at the microstructural level, can affect the prepared concrete substrate moisture condition. Adsorption may in fact prevent (temporarily or permanently) water from moving into the concrete.

Another important factor with regards to moisture transport mechanisms is water movement between the substrate and the repair material driven by thermal gradients: water will tend to move from warmer parts of the composite to the colder ones. As a result, this can increase the water to cementitious material (w/c) ratio, which may negatively affect the bond strength and durability.

Objective and Scope of the Project

The main objective of the study is to establish the optimum concrete substrate moisture condition prior to repair / overlay application to improve bond in composite repair systems.

For concrete repairs and overlays, bond strength is commonly defined as "the tensile strength perpendicular to the interface plane" and is usually evaluated using pull-off tests. However, shear stresses parallel to the interface can be equally important. Consequently, the bond strength in shear is a significant factor in composite repair systems. Hence, in addition to pull off tests, shear bond (torque) tests were performed on the test slabs (9 shear tests per slab) using the pulling device used for pull-off tests, but equipped with a special adapter for torque testing.

The specific objectives of the required testing and study are:

- To gain a better understanding of the transport mechanisms between repair materials and concrete substrates and the effects of the moisture state of the substrate on bond development.
- To develop a field method to evaluate quantitatively the actual moisture condition of concrete, which may allow for the determination of optimum conditions for a given concrete substrate
- To evaluate this method in the laboratory and under field conditions to determine its reliability, applicability and performance characteristics.
- To evaluate the effect of repair materials upon moisture conditioning of the substrate to achieve the optimum bond.
- To issue recommendations for the optimum moisture conditioning of concrete substrates and identify the needs for future testing in this area.

The overall study consists of four (4) tasks (making concrete test slabs at 2 locations, performing repairs at different surface moisture conditions, performing bond tests, and compiling results) which will extend over a three-year period. In this report, experimental results in Task 1 are presented.

Task 1 Description and Methodology

The scope of this task reported herein was to perform pull-off and shear tests on precast concrete slabs (48×20×5 in.) overlaid with cement-based repair materials. The variables studied in the test program were the following:

- Substrate concrete strength (3 cement-based concrete mixtures);
- Moisture conditioning of the substrate at the time of repair (3 levels of surface humidity);
- Repair material (2 cement-based repair concrete mixtures).

Before undertaking Task 1, twenty-five (25) concrete test slabs were cast on April 6 and April 19, 2012 using three different concrete mixtures:

- 3000-psi concrete (6 test slabs);
- 5000-psi concrete with 20 percent (%) fly ash (13 test slabs);
- 7000-psi silica fume (8 %) concrete (6 test slabs).

The tests slabs were stored in the 73 °Fahrenheit (F) (23 °Celcius (C)) and 50 % Relative Humidity (RH) conditioning room until May 1st, 2013. After one full year of conditioning, nineteen (19) of the test slabs (6 slabs from the 3000-psi series; 7 slabs from the 5000-psi series; 6 slabs from the 7000-psi series) were overlaid with a 2-in. layer of either one of the following cement-based repair materials:

- 5000-psi concrete mixture with 20 % fly ash (ready-mix concrete delivered on site);
- BASF *Zero C* extended mortar (proprietary material mixed on site).

The overall test program conducted as part of Task 1 is summarized in Table 1, where each test slab subset is identified using the following key:

MC – **X – Y – Repair material**

with **X**, **Y** and **Repair material** taking the following values:

X: **3** (3000-psi concrete);
5 (5000-psi concrete);
7 (7000-psi concrete);

Y: **0** (0-h long ponding);
1 (1-h long ponding);
6 (6-h long ponding);

Repair material: **CON** (5000-psi concrete with 20% fly ash);
BASF (BASF *Zero C* extended mortar).

For example, the **MC-3-1-BASF** slab is a 3000-psi test slab that was ponded for 1 hour (h) and repaired with the BASF extended mortar. For one combination (**MC-5-6-CON**), two (2) tests slabs were prepared, the second one being identified by the suffix (1). The same key will be used throughout this data report.

Prior to the repair material placement, each of the test slab series were conditioned in such a way to have three slab subsets with different moisture content at the surface. Based upon results generated in a previous study (4), three surface ponding durations were selected:

- 0 hour (no ponding / equilibrium water content at 50 % RH);
- 1 hour;
- 6 hours.

Table 1. Test program summary

Slab ID	Nominal Substrate Concrete Strength			Moisture conditioning duration			Overlay Material	
	3000 psi (21 MPa)	5000 psi (35 MPa)	7000 psi (48 MPa)	0 h	1 h	6 h	5000-psi concrete	BASF extended mortar
MC-3-0-CON	×			×			×	
MC-3-1-CON	×				×		×	
MC-3-6-CON	×					×	×	
MC-3-0-BASF	×			×				×
MC-3-1-BASF	×				×			×
MC-3-6-BASF	×					×		×
MC-5-0-CON		×		×			×	
MC-5-1-CON		×			×		×	
MC-5-6-CON		×				×	×	
MC-5-6-CON(1)		×				×	×	
MC-5-0-BASF		×		×				×
MC-5-1-BASF		×			×			×
MC-5-6-BASF		×				×		×
MC-7-0-CON			×	×			×	
MC-7-1-CON			×		×		×	
MC-7-6-CON			×			×	×	
MC-7-0-BASF			×	×				×
MC-7-1-BASF			×		×			×
MC-7-6-BASF			×			×		×

The composition details and characterization test results of all substrate concrete and overlay mixtures are summarized in Table 2.

Table 2. Substrate and overlay mixtures

Constituent	Quantity	Standard[1]	Concrete Mixture 3000 psi	Concrete Mixture 5000 psi	Concrete Mixture 7000 psi
Cement	lb/yd^3 (kg/m^3)	ASTM C 150	470 (279)	528 (313)	689 (409)
Fly Ash	lb/yd^3 (kg/m^3)	ASTM C 618	0 (0)	132 (78)	122 (72)
Coarse Aggregate	lb/yd^3 (kg/m^3)	ASTM C 33 (#57/67 - 3/4")	1788 (1061)	1812 (1075)	1646 (977)
Fine Aggregate	lb/yd^3 (kg/m^3)	ASTM C 33 (sand)	1295 (768)	1111 (66)	1192 (707)
AEA	oz/yd^3 (mL/m^3)	ASTM C 260	3.2 (126)	3.2 (126)	3.5 (137)
Low-Range WRA	oz/yd^3 (L/m^3)	ASTM C 494 (Type A)	0 (0)	0 (0)	48.6 (1.91)
Mid-Range WRA	oz/yd^3 (L/m^3)	ASTM C 494 (Type A/F)	18.8 (0.74)	39.6 (1.55)	81 (3.18)
High-Range WRA	oz/yd^3 (L/m^3)	ASTM C 494 (Type F)	0 (0)	0 (0)	0 (0)
Water	lb/yd^3 (kg/m^3)	Potable Water	273 (162)	257 (152)	243 (144)
Specifications					
Air Content	(%)	ASTM C 231	4 - 7	4 - 7	4 - 7
w/cm Ratio	-		0.58	0.39	0.30
Slump	in (mm)	ASTM C 143	4 (100)	4 (100)	4 (100)
Unit Weight	lb/ft^3 (kg/m^3)	ASTM C 138	141.2 (2262)	141.7 (2270)	143.6 (2301)
Fine/coarse Agg. Ratio	-		0.42	0.38	0.42
Characterization					
Compressive strength		ASTM C 39			
$f_{c\ 4\text{-}d}$ substrate	psi (MPa)			- -	
$f_{c\ 4\text{-}d}$ repair	psi (MPa)			3495 (24.1)	
$f_{c\ 7\text{-}d}$ substrate	psi (MPa)			4065 (28.0)	
$f_{c\ 7\text{-}d}$ repair	psi (MPa)			3795 (26.2)	
$f_{c\ 28\text{-}d}$ substrate	psi (MPa)		4845 (33.4)	5615 (38.7)	7425 (51.2)
$f_{c\ 28\text{-}d}$ repair	psi (MPa)		- -	5350 (37.9)	- -
$f_{c\ 56\text{-}d}$ substrate	psi (MPa)			5700 (39.3)	
$f_{c\ 56\text{-}d}$ repair	psi (MPa)			- -	

Two methods assessed in a previous study (5) were used to evaluate the moisture content on the surface of the concrete substrate at the time of repair overlay placement on all 19 slabs, namely an electrical impedance surface meter and embedded relative humidity probes (*RH meters*), as shown in Figure 1. Measurements were performed at different key moments. Moisture contents recorded in the various slabs prior to moisture treatment, right after the

[1] See Reference standards in Section 7

moisture treatments, at the time of overlay placement and at the time of bond testing are summarized in Table 3.

Figure 1. Devices used to monitor the moisture condition in the surface layer of the concrete specimens: a) electrical impedance surface moisture meter; b) embedded relative humidity probes

Table 3. Moisture conditioning test results

Slab ID	Moisture condition						
	Electrical Impedance Method (device reading units)			RH Probe Percent (%)			
	Prior to moisture treatment	After moisture treatment	At time of overlay placement	Prior to moisture treatment	After moisture treatment	At time of overlay placement	At time of bond testing
MC-3-0-CON	1.1	1.0	0.5	50	67	66	79
MC-3-1-CON	2.5	6.9	1.1	50	67	75	80
MC-3-6-CON	2.3	6.9	1.4	50	73	72	80
MC-3-0-BASF	0.5	0.5	n/a	50	64	n/a	n/a
MC-3-1-BASF	2.0	6.9	0.5	50	n/a	n/a	n/a
MC-3-6-BASF	1.8	6.1	0.5	50	73	n/a	n/a
MC-5-0-CON	1.9	0.6	0.4	50	61	60	78
MC-5-1-CON	2.0	5.4	0.9	50	63	64	76
MC-5-6-CON	2.1	6.9	0.8	50	69	73	80
MC-5-6-CON(1)	1.7	6.9	0.3	50	68	80	n/a
MC-5-0-BASF	1.8	0.5	n/a	50	62	n/a	n/a
MC-5-1-BASF	1.9	6.9	0.5	50	n/a	n/a	n/a
MC-5-6-BASF	1.8	1.4	0.8	50	n/a	n/a	n/a
MC-7-0-CON	2.5	1.1	0.7	50	62	61	76
MC-7-1-CON	2.4	6.9	0.9	50	57	61	82
MC-7-6-CON	2.2	6.9	1.0	50	67	68	80
MC-7-0-BASF	2.3	0.5	n/a	50	63	n/a	n/a
MC-7-1-BASF	2.7	6.9	0.9	50	60	n/a	n/a
MC-7-6-BASF	2.8	6.4	0.8	50	n/a	n/a	n/a

After overlays (repairs) were placed on test slabs by MERL personnel and cured for a period ranging between 28 and 56 days, pull off bond and shear bond testing were performed on 19 concrete slabs at MERL in Denver. Bond testing of each slab consisted generally of nine (9) pull off tests and nine (9) shear tests, distributed in accordance with the layout shown in Figure 2. Overall, a total of 347 tests (174 pull off bond tests, 173 shear bond tests) were performed. The task was carried out within a two-week period early in May 2013. All work was accomplished with MERL personnel present. Photographs displayed in Figures 2 to 6 show the various operations involved in the bond testing program.

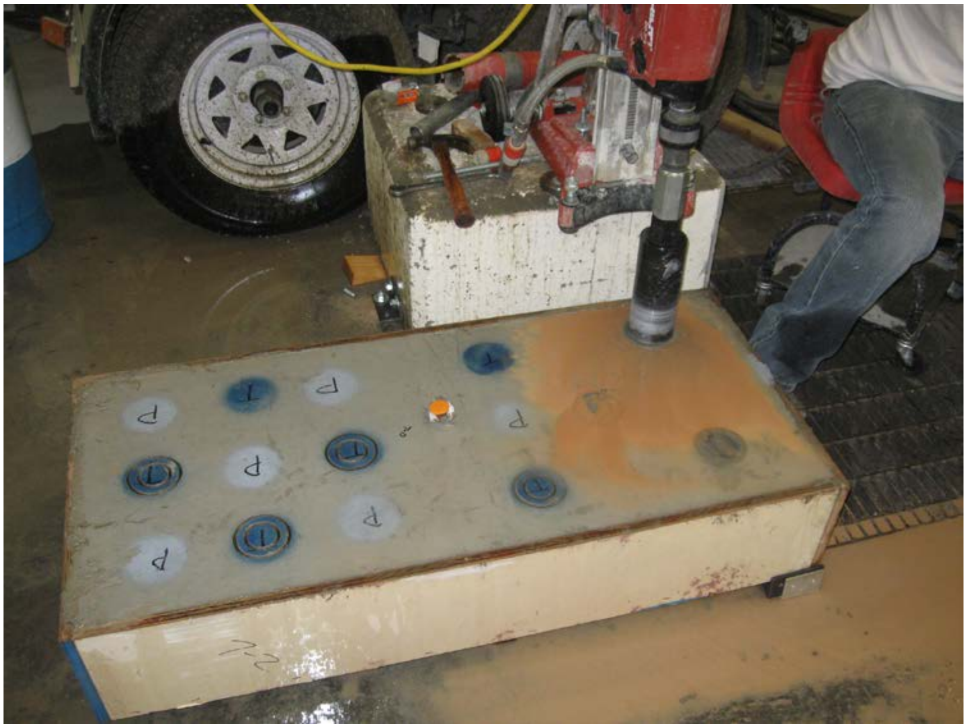

Figure 2. Experimental bond testing preparation (coring template and jig assembly)

Figure 3. Cored test slab prior to bond testing
(single coring: tensile bond; dual coring: shear bond)

Figure 4. Direct tension bond testing (tensile bond) procedure

Figure 5. Torque bond testing (shear bond) procedure

a) 

b) 

Figure 6. Bond test specimens after failure : a) direct tension loading; b) torque loading

As a third-party collaborator, the U.S. Navy intended to perform similar experiments (complementary program) at their facility using their staff and provide MERL with test results in order to add them to the body of data generated at MERL. However, the test program planned at the Navy could not be performed within the Task 1 schedule.

Test results

The test results generated as part of Task 1 are summarized in Tables 4 to 22 and in bar charts of Figures 7 to 12.

Table 4. Bond Test Results: Slab MC-3-0-CON

Shear bond strength - Slab MC-3-0-CON				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode**	**Observations**
1				Interface debonding while drilling.
3	184.2	1.27	substrate	
5	276.3	1.91	substrate/repair	
7				Interface debonding while drilling.
9	83.7	0.58	interface	
11	200.9	1.39	substrate	
13	163.2	1.13	substrate	
15	125.5	0.87	substrate/int	
17	142.3	0.98	susbtrate	
Average	**168.0**	**1.16**	**Repair (%)***	14.3
Std. Deviation	61.5	0.42	**Interface (%)**	28.6
COV (%)	36.6		**Substrate (%)**	57.1

* Percent bond failure in the repair material, at the interface, or in the surbtrate.

Pull off bond strength - Slab MC-3-0-CON				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode**	**Observations**
2	311.6	2.15	substrate	
4	168.5	1.16	interface	
6	241.6	1.67	interface	
8	219.4	1.51	interface	Epoxy failure on 1st attempt (4.7 kN).
10	257.5	1.78	substrate	
12	257.5	1.78	interface	
14	120.8	0.83	interface	
16	206.7	1.43	interface	
18	292.5	2.02	interface	
Average	**230.7**	**1.59**	**Repair (%)**	0.0
Std. Deviation	59.8	0.41	**Interface (%)**	77.8
COV (%)	25.9		**Substrate (%)**	22.2

Table 5. Bond Test Results: Slab MC-3-1-CON

Shear bond strength - Slab MC-3-1-CON				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode**	**Observations**
1	92.0	0.63	substrate/int	
3	133.9	0.92	substrate/repair	
5				Interface debonding while drilling.
7	92.0	0.63	interface	
9	163.2	1.13	substrate/int	
11				Coring not deep enough.
13	180.0	1.24	substrate	
15	154.9	1.07	substrate	
17	159.0	1.10	substrate	
Average	**139.3**	**0.96**	**Repair (%)**	14.3
Std. Deviation	35.0	0.24	**Interface (%)**	42.9
COV (%)	25.1		**Substrate (%)**	42.9

Pull off bond strength - Slab MC-3-1-CON				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode**	**Observations**
2	235.3	1.62	interface	
4	317.9	2.19	repair	
6	165.3	1.14	interface	
8	289.3	2.00	substrate	
10	257.5	1.78	interface	
12	267.1	1.84	substrate	
14	327.5	2.26	repair	
16	286.1	1.97	substrate	
18	225.7	1.56	interface	
Average	**263.5**	**1.82**	**Repair (%)**	22.2
Std. Deviation	50.2	0.35	**Interface (%)**	44.4
COV (%)	19.0		**Substrate (%)**	33.3

Table 6. Bond Test Results: Slab MC-3-6-CON

Shear bond strength - Slab MC-3-6-CON				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode**	**Observations**
1	163.2	1.13	substrate/repair	
3	251.2	1.73	substrate	
5	159.0	1.10	substrate	
7	146.5	1.01	substrate	
9	200.9	1.39	substrate	
11				Interface debonding while drilling.
13				Interface debonding while drilling.
15	163.2	1.13	substrate	
17	96.2	0.66	substrate	
Average	**168.6**	**1.16**	**Repair (%)**	14.3
Std. Deviation	47.8	0.33	**Interface (%)**	0.0
COV (%)	28.4		**Substrate (%)**	85.7

Pull off bond strength - Slab MC-3-6-CON				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode**	**Observations**
2	317.9	2.19	substrate	
4	330.6	2.28	substrate	
6	324.3	2.24	substrate	
8	337.0	2.32	substrate	
10	289.3	2.00	substrate	
12	356.1	2.46	substrate	
14	298.9	2.06	repair	
16	302.0	2.08	substrate	
18	362.4	2.50	substrate	
Average	**324.3**	**2.24**	**Repair (%)**	11.1
Std. Deviation	25.2	0.17	**Interface (%)**	0.0
COV (%)	7.8		**Substrate (%)**	88.9

Table 7. Bond Test Results: Slab MC-3-0-BASF

Shear bond strength - Slab MC-3-0-BASF				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode**	**Observations**
2	184.2	1.27	substrate	
4	255.3	1.76	substrate	
6	167.4	1.15	substrate	
8	209.3	1.44	substrate	
10	242.8	1.67	substrate	
12	318.2	2.19	substrate/int	
14	251.2	1.73	substrate	
16	263.7	1.82	substrate	
18	293.0	2.02	substrate	
Average	**242.8**	**1.67**	**Repair (%)**	0.0
Std. Deviation	48.9	0.34	**Interface (%)**	22.2
COV (%)	20.1		**Substrate (%)**	88.9

Pull off bond strength - Slab MC-3-0-BASF				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode**	**Observations**
1	330.6	2.28	repair	
3	302.0	2.08	substrate	
5	321.1	2.21	substrate	
7	340.2	2.35	substrate	
9	257.5	1.78	substrate	
11	311.6	2.15	substrate	
13	337.0	2.32	substrate	
15	270.2	1.86	substrate	
17	330.6	2.28	substrate	
Average	**311.2**	**2.15**	**Repair (%)**	0.0
Std. Deviation	29.6	0.20	**Interface (%)**	11.1
COV (%)	9.5		**Substrate (%)**	88.9

Table 8. Bond Test Results: Slab MC-3-1-BASF

Shear bond strength - Slab MC-3-1-BASF				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode**	**Observations**
1	100.4	0.69	substrate	
3	284.7	1.96	substrate/int	
5	209.3	1.44	substrate	
9	209.3	1.44	substrate	
11	192.5	1.33	substrate	
13	129.7	0.89	substrate	
15	247.0	1.70	substrate/int	
16	280.5	1.93	substrate	
17	121.4	0.84	substrate	
Average	**197.2**	**1.36**	**Repair (%)**	0.0
Std. Deviation	68.0	0.47	**Interface (%)**	22.2
COV (%)	34.5		**Substrate (%)**	77.8

Pull off bond strength - Slab MC-3-1-BASF				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode**	**Observations**
2	372.0	2.57	substrate	
4	327.5	2.26	substrate	
6	235.3	1.62	substrate	
7	419.7	2.89	repair	
8	349.7	2.41	susbtrate	Epoxy failure on 1st attempt (6,0 kN).
10	263.9	1.82	substrate	
12	391.1	2.70	repair	
14	359.3	2.48	substrate	
18	378.3	2.61	substrate	
Average	**344.1**	**2.37**	**Repair (%)**	22.2
Std. Deviation	59.9	0.41	**Interface (%)**	0.0
COV (%)	17.4		**Substrate (%)**	77.8

Table 9. Bond Test Results: Slab MC-3-6-BASF

Shear bond strength - Slab MC-3-6-BASF				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode**	**Observations**
1	251.2	1.73	susbtrate	
3	217.7	1.50	substrate/int	
5	205.1	1.41	substrate	
7	247.0	1.70	substrate	
9	159.0	1.10	substrate	
11	226.0	1.56	substrate	
13	234.4	1.62	substrate	
15	192.5	1.33	substrate	
17	184.2	1.27	substrate	
Average	**213.0**	**1.47**	**Repair (%)**	0.0
Std. Deviation	30.6	0.21	**Interface (%)**	22.2
COV (%)	14.4		**Substrate (%)**	88.9

Pull off bond strength - Slab MC-3-6-BASF				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode**	**Observations**
2	251.2	1.73	susbtrate	
4	352.9	2.43	substrate	
6	362.4	2.50	substrate	
8	317.9	2.19	substrate	
10	295.7	2.04	substrate	
12	378.3	2.61	½ int / ½ subst	
14	352.9	2.43	substrate	
16	302.0	2.08	substrate	
18	400.6	2.76	substrate	
Average	**334.9**	**2.31**	**Repair (%)**	0.0
Std. Deviation	46.8	0.32	**Interface (%)**	11.1
COV (%)	14.0		**Substrate (%)**	88.9

Table 10. Bond Test Results: Slab MC-5-0-CON

Shear bond strength - Slab MC-5-0-CON				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode**	**Observations**
2	58.5	0.40	interface	
4	117.2	0.81	susbtrate	
6	138.1	0.95	interface	
8	163.2	1.13	substrate	
10	276.3	1.91	substrate/int	
12	188.4	1.30	substrate/repair	
14	104.6	0.72	substrate/int	
16	205.1	1.41	substrate	
18				Interface debonding while drilling.
Average	**156.4**	**1.08**	**Repair (%)**	12.5
Std. Deviation	67.6	0.47	**Interface (%)**	50.0
COV (%)	43.2		**Substrate (%)**	37.5

Pull off bond strength - Slab MC-5-0-CON				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode**	**Observations**
1	60.4	0.42	interface	
3	362.4	2.50	½ int / ½ subst	
5	362.4	2.50	substrate	
7	327.5	2.26	interface	
9	324.3	2.24	interface	
11	368.8	2.54	repair	
13	273.4	1.89	repair	
15	127.2	0.88	interface	
17	206.7	1.43	interface	
Average	**268.1**	**1.85**	**Repair (%)**	22.2
Std. Deviation	112.6	0.78	**Interface (%)**	66.7
COV (%)	42.0		**Substrate (%)**	11.1

Table 11. Bond Test Results: Slab MC-5-1-CON

Shear bond strength - Slab MC-5-1-CON				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode**	**Observations**
2	159.0	1.10	substrate	
4	12.5	0.09	substrate/int	
6	146.5	1.01	substrate/int	
8	200.9	1.39	substrate	
10	87.9	0.61	interface	
12	83.7	0.58	interface	
14	200.9	1.39	substrate/repair	
16	192.5	1.33	substrate/repair	
18	20.9	0.14	substrate/int	
Average	**122.8**	**0.85**	**Repair (%)**	22.2
Std. Deviation	74.4	0.51	**Interface (%)**	55.6
COV (%)	60.6		**Substrate (%)**	22.2

Pull off bond strength - Slab MC-5-1-CON				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode**	**Observations**
1	162.1	1.12	interface	
3	263.9	1.82	interface	
5	292.5	2.02	substrate	
7	190.8	1.32	interface	
9	305.2	2.11	interface	
11	286.1	1.97	interface	
13	292.5	2.02	interface	
15	298.9	2.06	substrate	
17	435.6	3.00	interface	
Average	**280.8**	**1.94**	**Repair (%)**	0.0
Std. Deviation	77.2	0.53	**Interface (%)**	77.8
COV (%)	27.5		**Substrate (%)**	22.2

Table 12. Bond Test Results: Slab MC-5-6-CON

Shear bond strength - Slab MC-5-6-CON				
Core #	Bond strength (psi)	(MPa)	Failure mode	Observations
2	150.7	1.04	substrate	
4	159.0	1.10	substrate	
6	175.8	1.21	substrate	
8	184.2	1.27	substrate/repair	
10	247.0	1.70	substrate/int	
12	159.0	1.10	interface	
14	238.6	1.65	substrate/repair	
16	221.8	1.53	substrate	
18	217.7	1.50	substrate	
Average	**194.9**	**1.34**	**Repair (%)**	22.2
Std. Deviation	36.9	0.25	**Interface (%)**	22.2
COV (%)	18.9		**Substrate (%)**	55.6

Pull off bond strength - Slab MC-5-6-CON				
Core #	Bond strength (psi)	(MPa)	Failure mode	Observations
1	330.6	2.28	repair	
3	292.5	2.02	substrate	
5	283.0	1.95	substrate	
7	149.4	1.03	interface	
9	251.2	1.73	interface	
11	378.3	2.61	½ int / ½ repair	
13	340.2	2.35	interface	
15	276.6	1.91	interface	
17	241.6	1.67	interface	
Average	**282.6**	**1.95**	**Repair (%)**	11.1
Std. Deviation	66.5	0.46	**Interface (%)**	66.7
COV (%)	23.5		**Substrate (%)**	22.2

Table 13. Bond Test Results: Slab MC-5-0-CON(1)

Shear bond strength - Slab MC-5-6-CON (1)				
Core #	Bond strength (psi)	(MPa)	Failure mode	Observations
1	255.3	1.76	substrate	
3	318.2	2.19	substrate/int	
5	221.8	1.53	substrate	
7	108.8	0.75	substrate	
9	217.7	1.50	substrate/int	
11	284.7	1.96	substrate	
13	117.2	0.81	substrate	
15	276.3	1.91	substrate/int	
17	200.9	1.39	substrate/int	
Average	**222.3**	**1.53**	**Repair (%)**	0.0
Std. Deviation	72.0	0.50	**Interface (%)**	44.4
COV (%)	32.4		**Substrate (%)**	55.6

Shear bond strength - Slab MC-5-6-CON (1)				
Core #	Bond strength (psi)	(MPa)	Failure mode	Observations
1	255.3	1.76	substrate	
3	318.2	2.19	substrate/int	
5	221.8	1.53	substrate	
7	108.8	0.75	substrate	
9	217.7	1.50	substrate/int	
11	284.7	1.96	substrate	
13	117.2	0.81	substrate	
15	276.3	1.91	substrate/int	
17	200.9	1.39	substrate/int	
Average	**222.3**	**1.53**	**Repair (%)**	0.0
Std. Deviation	72.0	0.50	**Interface (%)**	44.4
COV (%)	32.4		**Substrate (%)**	55.6

Table 14. Bond Test Results: Slab MC-5-0-BASF

Shear bond strength - Slab MC-5-0-BASF				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode**	**Observations**
1	334.9	2.31	substrate/int	
3	314.0	2.17	substrate/int	
5	293.0	2.02	substrate	
7	238.6	1.65	substrate/int	
9	230.2	1.59	substrate/int	
11	280.5	1.93	substrate/int	
13	163.2	1.13	substrate	
15	267.9	1.85	substrate	
17	360.0	2.48	substrate/int	
Average	**275.8**	**1.90**	**Repair (%)**	0.0
Std. Deviation	59.7	0.41	**Interface (%)**	66.7
COV (%)	21.7		**Substrate (%)**	33.3

Pull off bond strength - Slab MC-5-0-BASF				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode**	**Observations**
2	429.2	2.96	substrate	
4	457.8	3.16	repair	
6	368.8	2.54	½ int / ½ subst	
8	419.7	2.89	repair	
10	483.3	3.33	½ int / ½ subst	
12	454.6	3.14	substrate	
14	375.2	2.59	substrate	
16	457.8	3.16	substrate	
18	359.3	2.48	substrate	
Average	**422.8**	**2.92**	**Repair (%)**	22.2
Std. Deviation	45.3	0.31	**Interface (%)**	22.2
COV (%)	10.7		**Substrate (%)**	55.6

Table 15. Bond Test Results: Slab MC-5-1-BASF

Shear bond strength - Slab MC-5-1-BASF				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode**	**Observations**
1	230.2	1.59	substrate	
3	293.0	2.02	substrate	
5	200.9	1.39	substrate	
7	188.4	1.30	substrate	
9	234.4	1.62	substrate	
11	213.5	1.47	susbtrate	
13	226.0	1.56	substrate/int	
15	293.0	2.02	substrate/int	
17	108.8	0.75	substrate	
Average	**220.9**	**1.52**	**Repair (%)**	0.0
Std. Deviation	55.7	0.38	**Interface (%)**	22.2
COV (%)	25.2		**Substrate (%)**	77.8

Pull off bond strength - Slab MC-5-1-BASF				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode**	**Observations**
2	384.7	2.65	substrate	
4	403.8	2.78	substrate	
6	473.7	3.27	substrate	
8	346.5	2.39	½ int / ½ subst	
10	461.0	3.18	substrate	
12	451.5	3.11	substrate	
14	480.1	3.31	repair	
16	394.2	2.72	repair	
18	391.1	2.70	substrate	
Average	**420.7**	**2.90**	**Repair (%)**	22.2
Std. Deviation	46.9	0.32	**Interface (%)**	11.1
COV (%)	11.1		**Substrate (%)**	66.7

Table 16. Bond Test Results: Slab MC-5-6-BASF

Shear bond strength - Slab MC-5-6-BASF				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode**	**Observations**
2	263.7	1.82	substrate/int	
4	217.7	1.50	substrate	
6	196.7	1.36	substrate	
8	159.0	1.10	substrate	
10	242.8	1.67	substrate	
12	263.7	1.82	substrate	
14	192.5	1.33	substrate	
16	259.5	1.79	substrate	
18	184.2	1.27	substrate	
Average	**220.0**	**1.52**	**Repair (%)**	0.0
Std. Deviation	39.1	0.27	**Interface (%)**	11.1
COV (%)	17.8		**Substrate (%)**	88.9

Pull off bond strength - Slab MC-5-6-BASF				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode**	**Observations**
1	387.9	2.68	substrate	
3	327.5	2.26	substrate	
5	337.0	2.32	substrate	
7	330.6	2.28	substrate	
9	330.6	2.28	substrate	
11	333.8	2.30	substrate	
13	352.9	2.43	substrate	
15	387.9	2.68	substrate	
17	387.9	2.68	substrate	
Average	**352.9**	**2.43**	**Repair (%)**	0.0
Std. Deviation	27.2	0.19	**Interface (%)**	0.0
COV (%)	7.7		**Substrate (%)**	100.0

Table 17. Bond Test Results: Slab MC-7-0-CON

Shear bond strength - Slab MC-7-0-CON				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode**	**Observations**
2	305.6	2.11	substrate/int	
4	180.0	1.24	substrate/repair	
6	247.0	1.70	substrate/repair	
8	226.0	1.56	interface/repair	
10	184.2	1.27	substrate/repair	
12	226.0	1.56	substrate/int	
14	221.8	1.53	substrate	
16	163.2	1.13	interface/repair	
18	217.7	1.50	substrate	
Average	**219.1**	**1.51**	**Repair (%)**	33.3
Std. Deviation	42.2	0.29	**Interface (%)**	44.4
COV (%)	19.3		**Substrate (%)**	22.2

Pull off bond strength - Slab MC-7-0-CON				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode**	**Observations**
1	35.0	0.24	interface	
3	352.9	2.43	repair	
5	365.6	2.52	repair	
7	54.0	0.37	interface	
9	384.7	2.65	repair	
11	311.6	2.15	interface	
13	302.0	2.08	repair	
15	359.3	2.48	repair	
17	368.8	2.54	repair	
Average	**281.5**	**1.94**	**Repair (%)**	66.7
Std. Deviation	137.1	0.95	**Interface (%)**	33.3
COV (%)	48.7		**Substrate (%)**	0.0

Table 18. Bond Test Results: Slab MC-7-1-CON

Shear bond strength - Slab MC-7-1-CON				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode**	**Observations**
1				Interface debonding while drilling.
3	200.9	1.39	substrate/repair	
5	272.1	1.88	substrate	
7				Interface debonding while drilling.
9	263.7	1.82	substrate/repair	
11	54.4	0.37	interface/repair	
13	146.5	1.01	interface/repair	
15	117.2	0.81	substrate/int	
17	25.1	0.17	interface	
Average	**154.3**	**1.06**	**Repair (%)**	28.6
Std. Deviation	96.7	0.67	**Interface (%)**	57.1
COV (%)	62.7		**Substrate (%)**	14.3

Pull off bond strength - Slab MC-7-1-CON				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode**	**Observations**
2	372.0	2.57	repair	
4	89.0	0.61	interface	
6	372.0	2.57	repair	
8	352.9	2.43	repair	
10	187.6	1.29	interface	
12				Interface debonding while drilling.
14	349.7	2.41	interface	
16	292.5	2.02	interface	
18	85.8	0.59	interface	
Average	**262.7**	**1.81**	**Repair (%)**	37.5
Std. Deviation	124.0	0.85	**Interface (%)**	62.5
COV (%)	47.2		**Substrate (%)**	0.0

Table 19. Bond Test Results: Slab MC-7-6-CON

Shear bond strength - Slab MC-7-6-CON				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode**	**Observations**
2				Interface debonding while drilling.
4				Interface debonding while drilling.
6	154.9	1.07	substrate/int	
8	180.0	1.24	substrate/repair	
10				Interface debonding while drilling.
12				Interface debonding while drilling.
14				Interface debonding while drilling.
16	196.7	1.36	substrate/repair	
18				Interface debonding while drilling.
19	146.5	1.01	interface/repair	
21	125.5	0.87	substrate/int	
23	301.4	2.08	substrate/int	
Average	**184.2**	**1.27**	**Repair (%)**	33.3
Std. Deviation	62.7	0.43	**Interface (%)**	66.7
COV (%)	34.0		**Substrate (%)**	0.0

Pull off bond strength - Slab MC-7-6-CON				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode**	**Observations**
1				Interface debonding while drilling.
3				Interface debonding while drilling.
5	352.9	2.43	repair	
7				Interface debonding while drilling.
9	302.0	2.08	repair	
11				Interface debonding while drilling.
13	359.3	2.48	repair	
15				Interface debonding while drilling.
17				Interface debonding while drilling.
20	244.8	1.69	interface	
22	76.3	0.53	interface	
24				Interface debonding while drilling.
Average	**267.1**	**1.84**	**Repair (%)**	60.0
Std. Deviation	116.2	0.80	**Interface (%)**	40.0
COV (%)	43.5		**Substrate (%)**	0.0

Table 20. Bond Test Results: Slab MC-7-0-BASF

Shear bond strength - Slab MC-7-0-BASF				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode**	**Observations**
1	309.8	2.14	substrate	
3	146.5	1.01	substrate	
5	263.7	1.82	substrate/int	
7	276.3	1.91	substrate/int	
9	221.8	1.53	substrate	
11	280.5	1.93	substrate	
13	251.2	1.73	substrate/repair	
15	339.1	2.34	substrate	
17	138.1	0.95	substrate	
Average	**247.4**	**1.71**	**Repair (%)**	11.1
Std. Deviation	68.3	0.47	**Interface (%)**	22.2
COV (%)	27.6		**Substrate (%)**	66.7

Pull off bond strength - Slab MC-7-0-BASF				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode**	**Observations**
2	254.3	1.75	repair	
4	349.7	2.41	repair	
6	232.1	1.60	substrate	
8	232.1	1.60	repair	
10	410.1	2.83	repair	
12	333.8	2.30	repair	
14	356.1	2.46	repair	
16	356.1	2.46	repair	
18	314.7	2.17	repair	
Average	**315.5**	**2.18**	**Repair (%)**	88.9
Std. Deviation	62.7	0.43	**Interface (%)**	0.0
COV (%)	19.9		**Substrate (%)**	11.1

Table 21. Bond Test Results: Slab MC-7-1-BASF

Shear bond strength - Slab MC-7-1-BASF				
Core #	Bond strength (psi)	(MPa)	Failure mode	Observations
2	188.4	1.30	substrate	
4	142.3	0.98	substrate	
6	297.2	2.05	substrate/int	
8	247.0	1.70	substrate	
10	247.0	1.70	substrate/int	
12	263.7	1.82	substrate	
14	297.2	2.05	substrate/int	
16	209.3	1.44	substrate	
18	213.5	1.47	substrate	
Average	**233.9**	**1.61**	**Repair (%)**	0.0
Std. Deviation	50.9	0.35	**Interface (%)**	33.3
COV (%)	21.8		**Substrate (%)**	66.7

Pull off bond strength - Slab MC-7-1-BASF				
Core #	Bond strength (psi)	(MPa)	Failure mode	Observations
1	406.9	2.81	repair	
3	511.9	3.53	repair	
5	445.1	3.07	substrate	
7	438.7	3.03	repair	
9	496.0	3.42	repair	
11	400.6	2.76	repair	
13	432.4	2.98	substrate	
15	476.9	3.29	substrate	
17	451.5	3.11	substrate	
Average	**451.1**	**3.11**	**Repair (%)**	55.6
Std. Deviation	37.8	0.26	**Interface (%)**	0.0
COV (%)	8.4		**Substrate (%)**	44.4

Table 22. Bond Test Results: Slab MC-7-6-BASF

Shear bond strength - Slab MC-7-6-BASF				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode**	**Observations**
1	192.5	1.33	substrate	
3	318.2	2.19	substrate/int	
5	293.0	2.02	substrate	
7	339.1	2.34	substrate	
9	330.7	2.28	substrate	
11	150.7	1.04	substrate	
13	205.1	1.41	substrate	
15	334.9	2.31	substrate/repair	
17	226.0	1.56	substrate	
Average	**265.6**	**1.83**	**Repair (%)**	11.1
Std. Deviation	72.2	0.50	**Interface (%)**	11.1
COV (%)	27.2		**Substrate (%)**	77.8

Pull off bond strength - Slab MC-7-6-BASF				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode**	**Observations**
2	473.7	3.27	repair	
4	397.4	2.74	repair	
6	435.6	3.00	repair	
8	451.5	3.11	repair	
10	470.5	3.25	repair	
12	263.9	1.82	substrate	
14	314.7	2.17	repair	
16	435.6	3.00	repair	
18	372.0	2.57	interface	
Average	**401.6**	**2.77**	**Repair (%)**	77.8
Std. Deviation	72.6	0.50	**Interface (%)**	11.1
COV (%)	18.1		**Substrate (%)**	11.1

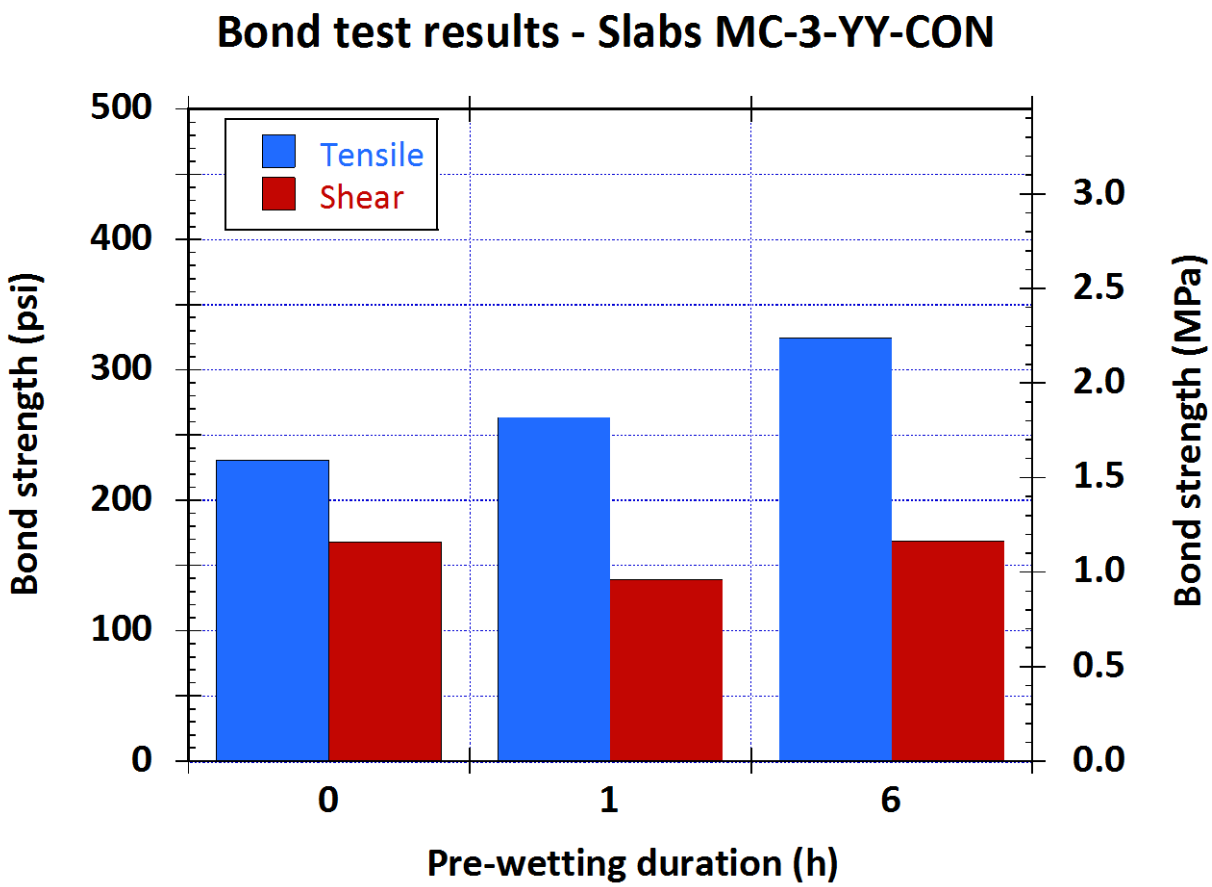

Figure 7. Experimental bond testing results for series MC-3-YY-CON

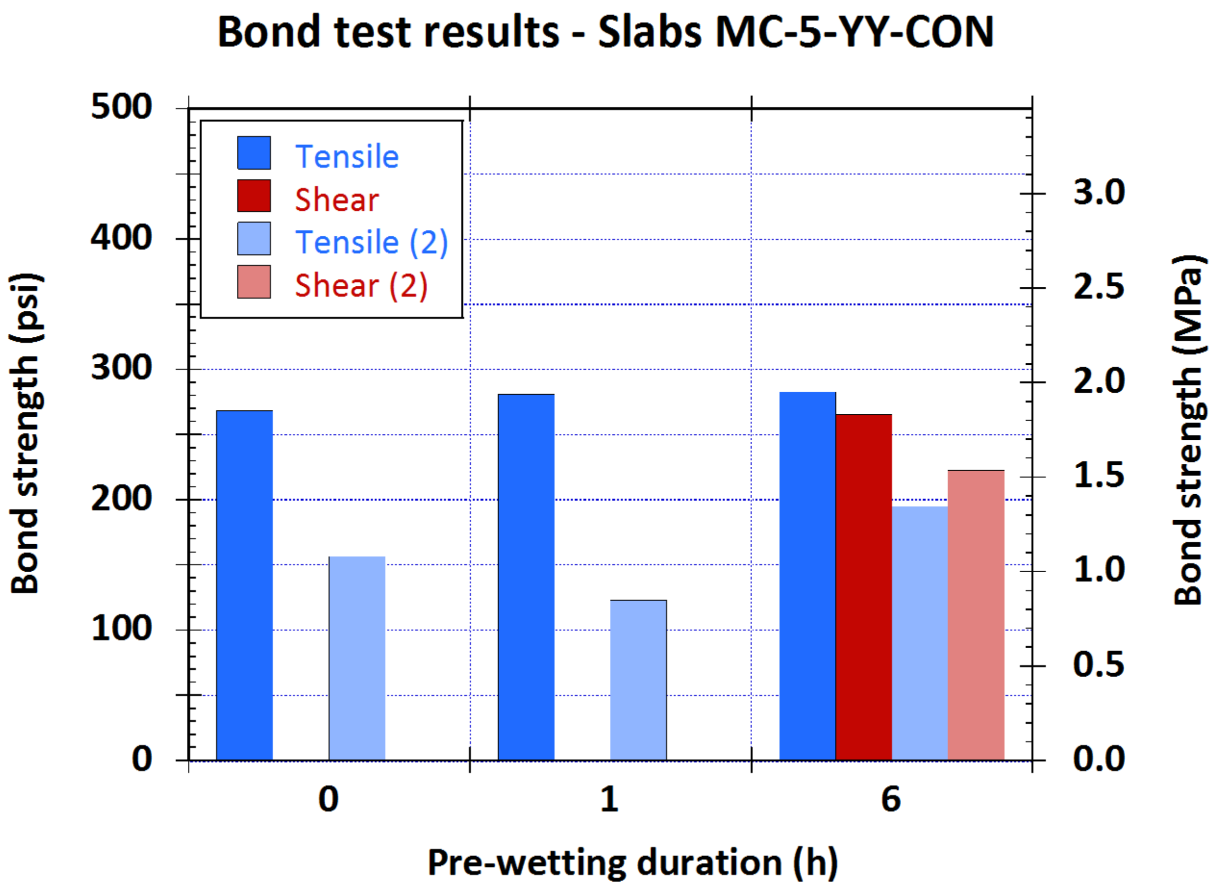

Figure 8. Experimental bond testing results for series MC-5-YY-CON. The (2) indicates results from the second test slab (Table 13).

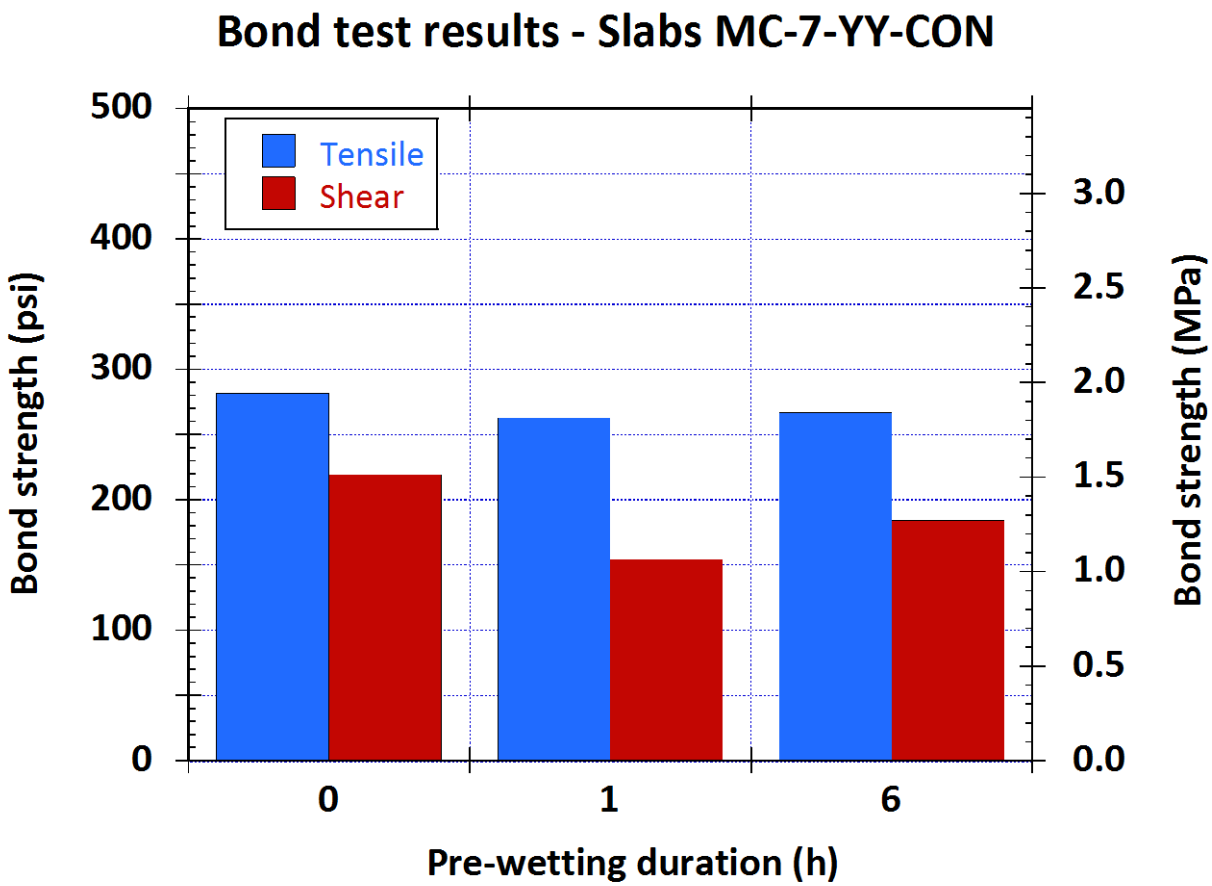

Figure 9. Experimental bond testing results for series MC-7-YY-CON

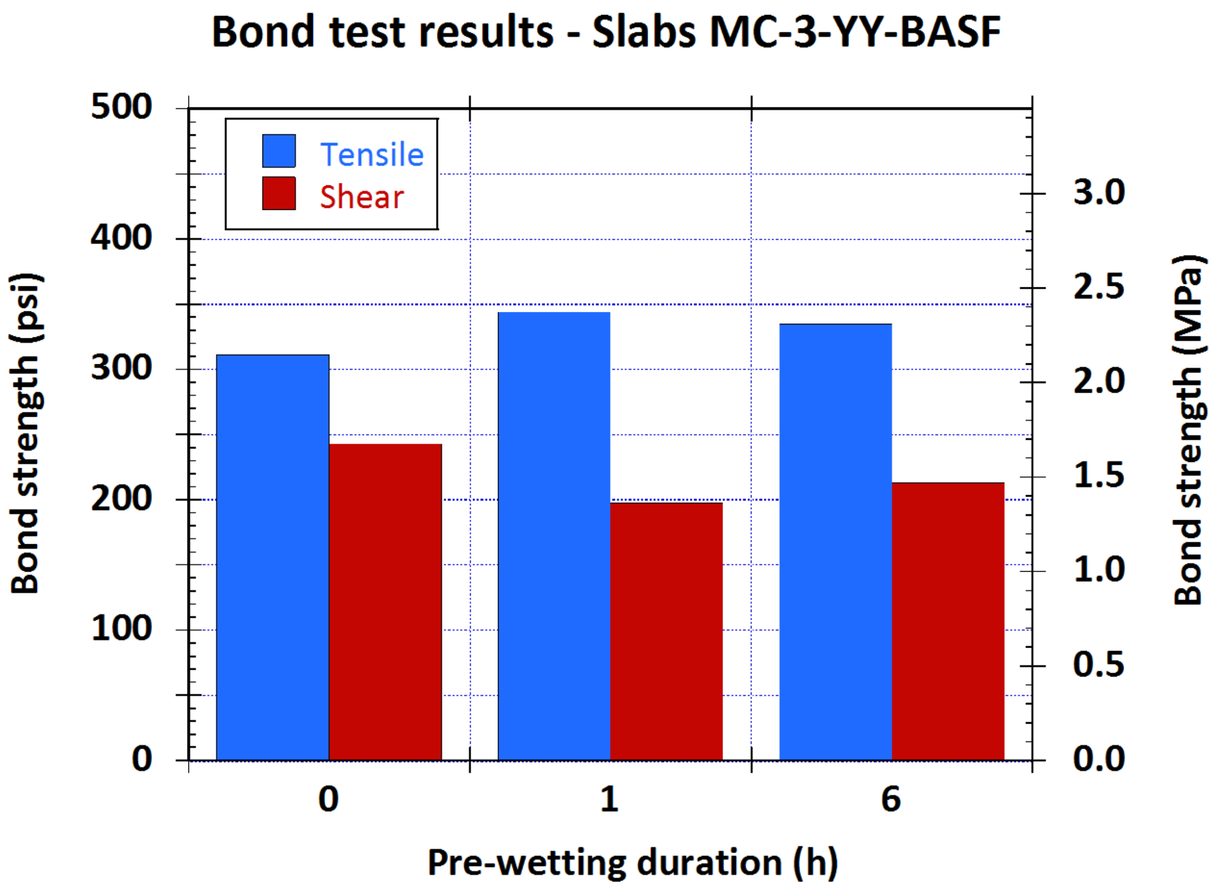

Figure 10. Experimental bond testing results for series MC-3-YY-BASF

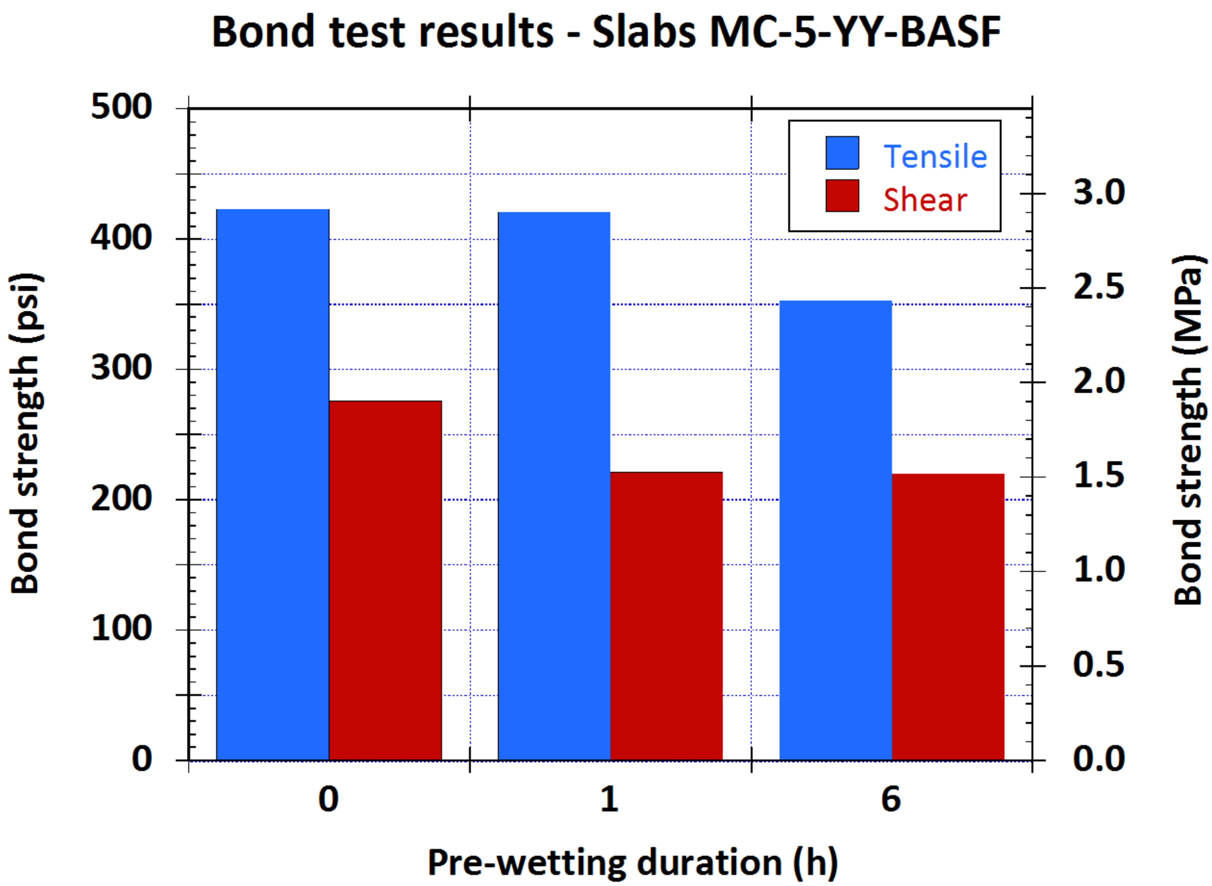

Figure 11. Experimental bond testing results for series MC-5-YY-BASF

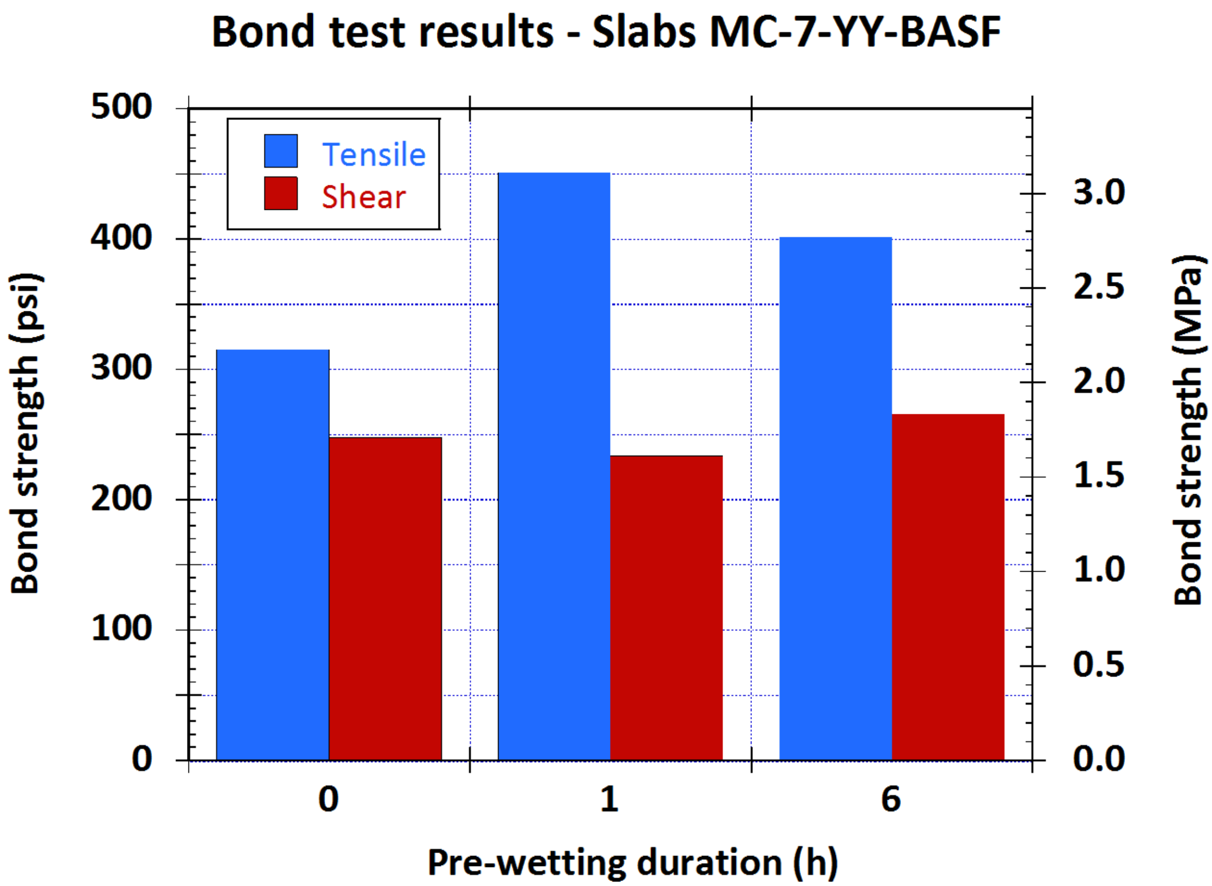

Figure 12. Experimental bond testing results for series MC-7-YY-BASF

Conclusion

The experimental work reported in this document will be followed by a second task involving bond testing of tests slabs conditioned for longer periods of time in a different environment.

The data generated in both Task 1 and Task 2 will then be analyzed to determine correlations between moisture content, bond strength, overlay material, and age of repair.

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Reference standards

ASTM International

ASTM C 33	Concrete Aggregates
ASTM C 39	Compressive Strength of Cylindrical Concrete Specimens
ASTM C 138	Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete
ASTM C 143	Slump of Hydraulic-Cement Concrete
ASTM C 150	Portland Cement
ASTM C 231	Air Content of Freshly Mixed Concrete by the Pressure Method
ASTM C 260	Air-Entraining Admixtures for Concrete
ASTM C 618	Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete