RECLAMATION

Managing Water in the West

Concrete Substrate Moisture Requirements for Effective Concrete Repairs

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Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

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Executive Summary

This report describes results from a 4-year project designed to develop guidelines for moisture conditioning of a concrete substrate prior to a cementitious repair, which was part of a larger effort to develop guidelines for surface preparation of concrete prior to repair (Bissonnette, Vaysburd, & von Fay, 2013) (Bissonnette, Vaysburd, & von Fay, 2012), (Vaysburd & Bissonnette, 2009) (Morency, Vaysburd, Bissonnette, & von Fay, 2007).

Over the course of this project, a variety of slabs were prepared for simulating an overlay repair under a variety of conditions. Bond strength tests were performed to measure the bond characteristics of the repair interface. From the test results, guidelines were developed relative to the types of materials used. In addition, findings showed that aspects of moisture conditioning deserve further study. The focus of this report are the studies that were performed this past year. Relevant results from previous years are also included where appropriate.

The development and magnitude of concrete repair bond strength and durability depend greatly on the concrete substrate surface preparation prior to the repair or overlay application. Unfortunately, for this very important parameter, only limited reliable guidance is available for the designer and practitioner. Design specifications and guidelines are commonly restricted to substrate concrete removal and cleaning methods, and to the achievement of a minimum mechanical bond strength value at 28 days, which is a short-term property that might not reflect the repair durability. The required moisture condition of the substrate, which may play an important role for bond development, and, ultimately, on the long-term repair / overlay durability, is generally ill-defined or addressed without any due consideration to the given substrate characteristics.

The influence of substrate surface moisture on the bond between the old existing concrete and the new repair material is an issue of significant importance. The standard specification, if any, is to specify the saturated surface dry (SSD) condition of the substrate prior to application of cementitious repair materials, which is theoretically achieved after saturating the substrate and then letting the surface just start to dry out. This does provide an intuitive solution to avoid problems, but it has never really been adequately defined, measured, nor tested.

The specific objectives of this study were:

- 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 investigate field methods to evaluate quantitatively the actual moisture condition of concrete, which is needed for the determination of optimum conditions for a given concrete substrate.
- To evaluate these moisture test methods in the laboratory and under field conditions to determine their reliability, applicability and performance characteristics.
- To evaluate the effect of repair materials upon moisture conditioning of the specific concrete substrate to achieve optimum bond.

- To issue recommendations for the optimum moisture conditioning of concrete substrates and identify the needs for future studies in this area, based on specific concrete substrates and specific repair materials used in this study.

For concrete repairs and overlays, both the tensile and shear bond strength are important characteristics. Hence, in addition to pull-off tests, shear bond (torque) tests were performed on laboratory test slabs, as part of the work conducted earlier in the research program (Bissonnette, Vaysburd, & von Fay, 2013). As no general correlation between the two physical characteristics could be established, it was decided to carry out only pull-off testing in the field test program.

The following conclusions and recommendations resulted from this project:

1. When normal and higher strength (about 5000 psi and higher) concrete elements are being repaired or overlaid with portland cement-based materials, then for the conditions in this investigation, pre-wetting of the substrate is not necessary for optimum bond strength.

2. When lower strength concrete elements are being repaired or overlaid, the optimum bond strength is obtained with extended water ponding, such as the 6-hour period used in this project.

3. Repair or overlay material proportioned to be low-shrinkage (materials which have shrinkage-compensating additives) under similar moisture conditioning of the concrete substrate results in higher bond strength when compared to ordinary concrete repair materials.

4. For the combination of materials and conditions investigated in the field program of this study, the maximum bond strength was reached relatively early, within the first two months after the repair.

5. The conclusions developed from this study are based on very specific combinations of substrates and repair materials and moisture conditioning times. Further studies on different combinations of repair materials and substrate concretes, with a range of ageing and water conditioning, is recommended. Unfortunately, it is clear that there is no such thing as a single universal optimum moisture condition that would apply to any combination of repair materials and existing concrete substrate.

6. Guidelines and codes need to be improved to clearly define what the SSD conditions really mean in existing concrete and, where desirable, to provide guidance on how it can be achieved, depending on the actual substrate concrete characteristics and condition.

7. Investigating conditions under which the moisture transport mechanisms between the existing concrete and the repair material are driven by temperature gradients is recommended. Water tends to move within a porous medium from warmer areas to cooler ones and this may well influence the interfacial repair bond development, depending on the exposure conditions.

8. Embedded relative humidity probes can be used effectively for field monitoring of relative humidity at the surface of a concrete element and determination of moisture condition.

9. In view of assessing the substrate moisture condition for concrete placement after pre-wetting, electrical impedance meters provide a promising alternative or complementary option to other approaches proposed in the forthcoming ACI 364 *Technote*.

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Introduction

Repair and strengthening of existing structures is one of the biggest challenges industrialized countries will face in the years to come. Also, the number of older concrete structures is increasing and so the needs for effective and long lasting 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 practice performing surface repairs and overlays in rehabilitation of existing concrete structures over the last 25 years, failures are still often observed. Irrespective of the methods or materials selected, a fundamental requirement for successful repair is the achievement of a strong and durable bond between the repair material and the existing concrete substrate. Monolithic action of the repaired structure is a pre-requisite for withstanding the imposed loads and resisting various concrete deterioration processes. The strength and integrity of the bond obviously depends on the properties and characteristics of the substrate concrete and repair material, but also to a significant degree on preparation and conditioning of the substrate surface to be repaired.

Concrete repair and rehabilitation commonly involves removing unsound concrete before the placement of a repair material. Regardless of the quality of the repair or overlay material used and application methods employed, the care with which concrete substrate is prepared and conditioned prior to the application of repair material will often determine whether a repair will be a success or a failure.

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

A concrete repair material bonded to the existing concrete is a composite material system. In such composites, the bond between the individual components is very critical for overall performance. The durability of the bond in the repair/existing concrete system can be defined as a lasting interfacial coexistence between the existing concrete and the repair material. However, when viewing this as a composite system, a high initial bond strength does not guarantee durability of the repair in service, since other factors can later weaken the bond.

Still, 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 repair system.

The development and magnitude of interfacial bond strength and bond durability depend to a great extent on the concrete substrate surface preparation prior to the repair or overlay application. Unfortunately, for this very important parameter, only limited reliable guidance is available for the designer and practitioner. Design specifications and guidelines are commonly restricted to substrate concrete removal and cleaning methods, and to the achievement of a minimum mechanical bond strength value at 28 days, which is a short-term property that might not reflect the repair durability. The required moisture condition of the substrate, which may play an important role for bond development, and, ultimately, on the long-term repair / overlay durability, is generally ill-defined or are addressed without any due consideration to the given substrate characteristics.

The influence of substrate surface moisture on the bond between the old existing concrete and the new repair material is an issue of significant importance. The standard specification, if any, is to specify the saturated surface dry (SSD) condition of the substrate prior to application of cementitious repair materials. This condition is theoretically achieved after saturating the substrate and then letting the surface just start to dry out. This does provide an intuitive solution to avoid problems, but has never been adequately defined, measured, nor tested. After all, there is no clear physical meaning of the SSD condition, neither qualitatively nor quantitatively, and there is 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 (RILEM TC 193 RLS, 2011), (Vaysburd, Emmons, Mailvaganam, McDonald, & Bissonnette, 2004), (Vaysburd, Sabnis, Emmons, & McDonald, Jan 2001), (Morency, Vaysburd, Bissonnette, & von Fay, 2007). 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 interfaces between existing and new phases of the composite. In particular, moisture condition of the substrate surface influences mass transport between the two phases forming the repair composite system. Reviewing available information shows that each given combination of existing concrete substrate and repair material may have very specific moisture condition requirements at the time of placement.

Mechanical adhesion in concrete members repaired 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 cement paste from the repair material mixture into the substrate, and it is strongly influenced by surface moisture conditions.

The substrate moisture condition influences the bond strength and durability in a variety of ways. A very dry "thirsty" concrete surface tends to "suck" water from the repair material, which may have both a negative and positive effect on bond strength depending on the magnitude of "suction" and amount of available moisture in the repair material. A surface, which is too wet, may dilute (increase the water to cementitious materials ratio) the repair material at the interface. To improve the performance of the composite concrete repair system, and in particular, the bond at the interface, it is essential to have 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, which 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) repair material water from moving into the concrete.

Another important factor regarding 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 / cementitious material ratio, which may negatively affect the bond strength and durability.

Objectives of the Research

The main objective of this study was to determine the optimum concrete substrate moisture condition prior to applying a repair or overlay material to ensure sufficient bond in the composite repair systems for a long lasting and durable repair.

The specific objectives of this study were:

- 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 investigate field methods to evaluate quantitatively the actual moisture condition of concrete, which is needed for the determination of optimum conditions for a given concrete substrate
- To evaluate moisture test methods in the laboratory and under field conditions to determine their reliability, applicability and performance characteristics.
- To evaluate the effect of repair materials upon moisture conditioning of the specific concrete substrate to achieve the optimum bond.
- To issue recommendations for the optimum moisture conditioning of concrete substrates and identify the needs for future studies in this area, based on specific concrete substrates and specific repair materials used in this study.

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 laboratory test slabs, in an earlier phase of this program ((Bissonnette, Vaysburd, & von Fay, 2013)). When considering the relationship between interfacial pull-off bond and shear bond strengths in composite repair overlay systems, the test results yielded in this research and in a complementary study (Bissonnette *et al*., 2016) do not exhibit the same trends as often reported or described in other studies. No general correlation between the two physical characteristics could actually be established, as different combinations of surface preparation parameters influence pull-off bond and shear bond strength measurements in different ways. Hence, in the field test program, it was decided to perform only pull-off testing.

Field Experiments

Description and Methodology

Before undertaking the field test program, three (3) concrete test slabs-on-grade (5 by 8 ft) were cast on December 4, 2014 using the basic BOR 5000 psi concrete mixtures used in previous part of this study (Bissonnette, Vaysburd, & von Fay, 2013). One of the outcomes of that work was to perform a series of tests on slabs that were conditioned in an outdoor environment. The size and strength of the slabs was influenced by results from those previous tasks. During the initial trials of this phase of the program, slabs were made a cured at a high elevation in the Colorado Rockies. However, due to technical difficulties, those slabs had to be abandoned and new slabs made in Denver, CO.

The tests slabs were stored outside at the Denver Federal Center, under a canopy, to protect them from direct precipitation. Shrinkage and moisture content were monitored at the surface of the slabs throughout the curing and conditioning period. After more than six months of exposure the test slabs were lightly sandblasted to create a consistent and adequate roughness of the surface. Prior to the repair material placement, as in the laboratory experiments, each slab was submitted to a specific moisture conditioning consisting in the following:

- no wetting;
- water ponding for one hour and air drying of the surface to yield SSD;
- water ponding for six hours and air drying of the surface to yield SSD.

The moisture condition of the surface prior to repair was evaluated with an electrical impedance meter. Based on previous works at Reclamation and Laval University (Vaysburd & Bissonnette, 2009)(Bissonnette, Vaysburd, & von Fay, 2013), the selected criterion for the SSD condition was a threshold value of 3.5.

The slabs were overlaid with a 2-in. layer of either one of the two following cement-based concrete materials, both incorporating 20 % of fly ash:

- 5000-psi BOR concrete mixture (ready-mix concrete delivered on site);
- 7000-psi BOR concrete mixture (ready-mix concrete delivered on site).

Each test slab was overlaid on one half (5 by 4 ft) with the 5000-psi concrete mixture, and on the other half with the 7000-psi concrete mixture. After overlaying, the slabs were moist cured for 7 days with clear plastic and then exposed to outdoor conditions (and under a canopy).

The overall test program conducted as part of the field experiment phase of the study is summarized in Table 1, where each test slab subset is identified using the following naming scheme (which is the naming scheme used in the previous reports of the research program, starting with the letters MC which stand for moist curing):

MC – X – Y – Z

with X, Y and Z representing the following:

X (concrete slab strength): 5 for the 5000-psi substrate concrete;

Y (pre-wetting time): 0 (no water ponding);
1 (1-h long water ponding, followed by superficial drying);
6 (6-h long water ponding, followed by superficial drying);

Z (repair material type and strength): CON 5 (5000-psi concrete);
CON 7 (7000-psi concrete).

For example, the MC-5-1-CON5 slab is a 5000 psi base slab that was ponded for 1 hour and repaired with the 5000 psi concrete. The same naming scheme will be used throughout this report.

Table 1- Field Trial Test Program Summary

Slab ID	Nominal Substrate Concrete Strength	Moisture Conditioning Duration			Overlay Material	
	5000 psi (35 MPa)	**0 h**	**1 h**	**6 h**	**5000-psi concrete**	**7000-psi concrete**
MC-5-0-CON5	✓	✓			✓	
MC-5-1-CON5	✓		✓		✓	
MC-5-6-CON5	✓			✓	✓	
MC-5-0-CON7	✓	✓				✓
MC-5-1-CON7	✓		✓			✓
MC-5-6-CON7	✓			✓		✓

For easy reference, a summary of the test program slabs and repairs conducted during the laboratory phase of the research project (Bissonnette, Vaysburd, & von Fay, 2013) is presented in Table 2.

Table 2- Test program conducted in the previous phase of the project

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 3.

Table 3. – Substrate and overlay mixtures

Constituent	Quantity		Standard	Concrete Mixture (*BESTWAY Concrete*)					
				5000 psi substrate		5000 psi repair		7000 psi repair	
Cement	lb/yd³	(kg/m³)	ASTM C150	528	(313)	528	(313)	689	(409)
Fly Ash	lb/yd³	(kg/m³)	ASTM C618	132	(78)	132	(78)	122	(72)
Coarse Aggregate	lb/yd³	(kg/m³)	ASTM C33 (#57/67 - 3/4")	1812	(1075)	1812	(1075)	1646	(977)
Fine Aggregate	lb/yd³	(kg/m³)	ASTM C33 (sand)	1111	(66)	1111	(66)	1192	(707)
AEA	oz/yd³	(mL/m³)	ASTM C260	3.2	(126)	3.2	(126)	4.0	(157)
Mid-Range WRA	oz/yd³	(L/m³)	ASTM C494 (Type A/F)	39.6	(1.55)	39.6	(1.55)	81	(3.18)
WRA / set-ret. admix.	oz/yd³	(L/m³)	ASTM C494	0	(0)	0	(0)	48.6	(1.91)
Set-retarding admix.	oz/yd³	(L/m³)	ASTM C494	29.7	(1.16)	29.7	(1.16)	36.5	(1.43)
Water	lb/yd³	(kg/m³)	Potable Water	257	(152)	257	(152)	243	(144)
Specifications									
Air Content	(%)		ASTM C231	4 - 7		4 - 7		4 - 7	
w/cm Ratio	-			0.39		0.39		0.30	
Slump	in	(mm)	ASTM C143	5	(125)	5	(125)	4	(100)
Unit Weight	lb/ft³	(kg/m³)	ASTM C138	141.7	(2270)	141.7	(2270)	143.6	(2301)
Fine/coarse Agg. Ratio	-			0.38		0.38		0.42	
Characterization									
Fresh concrete prop.									
Slump	in	(mm)		3.0	(75)	3.0	(75)	1.9	(50)
Air content	(%)					3.0		1.9	
Temperature	°F	(°C)		85	(29.5)	85	(29.5)	72	(22.5)
Compressive strength	psi	(MPa)	ASTM C39						
$f_{c\ 45\text{-}d}$						5690	(39.2)	7210	(49.7)
$f_{c\ 2\ months}$						5770	(39.8)	7155	(49.3)
$f_{c\ 8\ months}$				5350	(36.9)				
$f_{c\ 10\ months}$				6380	(44.0)				
$f_{c\ 12\ months}$						6800	(46.9)	8527	(58.8)
$f_{c\ 20\ months}$				5090	(35.1)				
Split.-tensile strength	psi	(MPa)	ASTM C39						
$f_{st\ 2\ months}$						350	(2.4)	420	(2.9)
$f_{c\ 10\ months}$				368	(2.5)				
$f_{st\ 12\ months}$						443	(3.1)	485	(3.3)
$f_{st\ 20\ months}$				285	(2.0)				

After applying the repair material, two sets of pull-off bond tests were performed on each test slab: a short-term set carried out at 2 months of age (September, 2015) and a long-term set carried out at one year of age (August, 2016). The tests were conducted in accordance with the coring layout shown in Figure 1. Overall, 272 tests (101 short-term pull-off tests, 171 long-term pull-off tests) were performed.

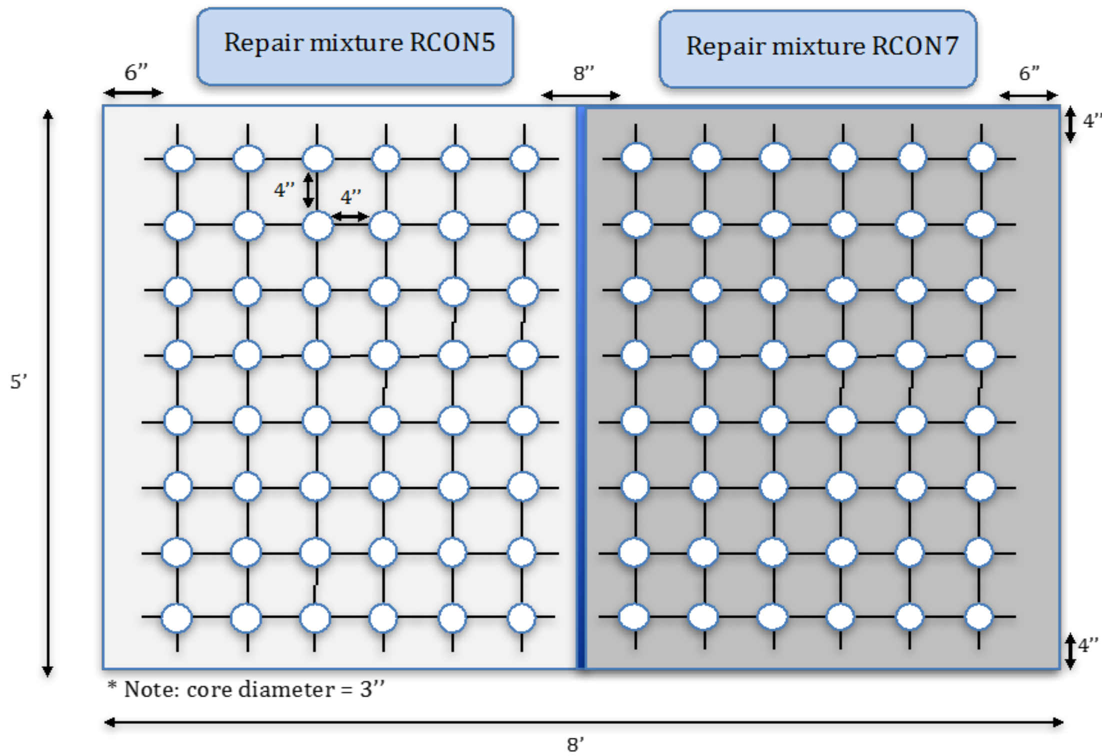


Figure 1. – Test slab coring layout for pull-off testing.

Appendix 1 shows photographs of the various operations involved in the field bond testing program.

It should be mentioned that the core distribution between short-term and long-term pull-off testing in each half-slab was selected randomly (see Appendix 1, Figures 19 to 21). After the short-term test series, the cores were filled with a repair mortar in order to prevent the potentially adverse effects of extensive drying of the interface in the neighboring long-term testing areas (see Appendix 1, Figures 22 to 27).

Moisture Conditioning of the Test Slabs

Two methods assessed previously in the research program were used to evaluate the moisture content on the surface of the concrete substrate at the time of repair / overlay placement on all 3 slabs, namely an electrical impedance surface meter and embedded relative humidity probes (*RH meters*), as shown in Figure 2. Moisture content was measured and recorded in the slabs prior to moisture treatment, right after the moisture treatments, and at the time of overlay placement (Figure 3 and **Table *4***).

a)

b)

Figure 2. – 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.

The slabs tested in the field program were not aged for an extended period of time. They were cured and aged for about 8 months, which occurred over the winter and during a particularly rainy spring season in Denver in 2015. The moisture content in the upper part of the test slabs at the time of repair had fallen below 85 %, according to the latest recordings shown in Figure 3. The bulk moisture content in the field test slabs was likely much higher than that of the slabs tested in the laboratory program (Bissonnette, Vaysburd, & von Fay, 2013).

Just prior to the placement of the repair material, two of the three slabs were moist conditioned for 1 and 6 hours respectively. Moist conditioning was carried by ponding. After the end of the ponding period, water was completely removed and the surface was exposed to air drying. Ready-mix trucks were ordered to arrive on site approximately 30 minutes after drying had begun. Based upon previous experiments at Reclamation and Laval University, the electrical impedance value corresponding to a surface moisture condition suitable for placement was set at 3.5. This threshold value was reached approximately 65 minutes after removal of water in the slab ponded for 1 hour, while it took 78 minutes in the slab ponded for 6 hours.

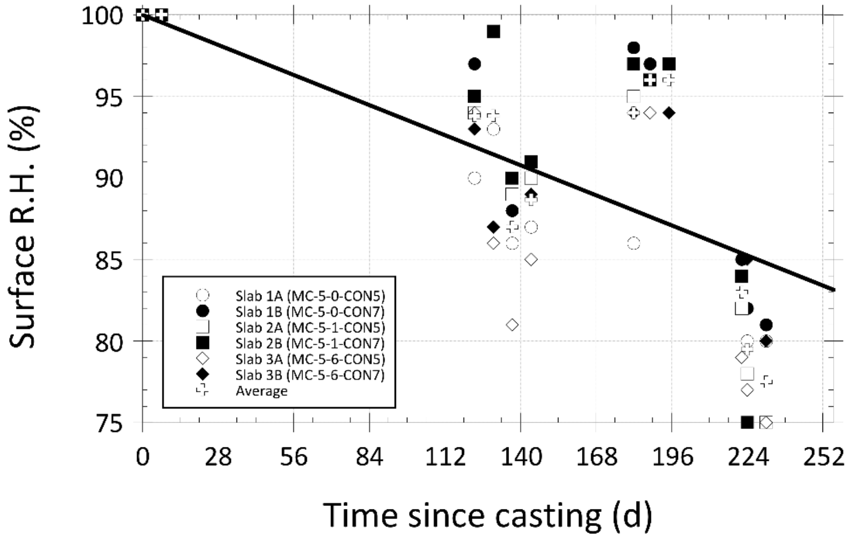


Figure 3. – Monitoring of relative surface moisture with relative humidity probes during the conditioning of the base test slabs.

Table 4. – Moisture conditioning test results

Slab ID	**Moisture condition**						
	Electrical Impedance Method (device reading units)			**RH Probe (%)**			
	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-5-0-CON5	2.5	-	2.5	75	n/a	n/a	n/a
MC-5-0-CON7	2.5	-	2.5	74	n/a	n/a	n/a
MC-5-1-CON5	3.2	3.7	3.5	75	n/a	n/a	n/a
MC-5-1-CON7	2.9	3.3	3.4	80	n/a	n/a	n/a
MC-5-6-CON5	2.9	3.6	3.4	80	n/a	n/a	n/a
MC-5-6-CON7	3.0	3.6	3.3	81	n/a	n/a	n/a

Test Results and Discussion

The main results from the field experiments carried out in this part of the research project are summarized in Table 5 to Table 10 and in Figure 4 to Figure 9. Appendix 2 shows tables with all the individual pull-off test results. In general, excellent bond was achieved, with a low rate of failure occurring away from the substrate.

In Table 11, the bond test results yielded from the field test program are summarized with the data generated previously in the laboratory experiments. For sake of comparison, the series MC-5-XX-CON and MC-5-XX-CON5 were identical combinations of the same substrate concrete and repair material (BOR 5000 psi concrete).

When addressing the influence of the substrate concrete moisture condition on bond of the repair, basic factors related to the porous nature of the material must be considered.

In fact, the moisture condition of the substrate surface heavily influences mass transport between the two phases (repair material and substrate concrete) forming the repair system composite. Mechanical adhesion in the substrate – repair/overlay systems relies on the penetration and hardening of the initially semi-liquid mixture inside the open micro-cavities and open pores of the prepared substrate concrete surface and the physical anchorage resulting from that.

There are two main processes that usually govern the moisture transport mechanisms at the interface: absorption and adsorption. Capillary absorption plays an important role in the anchorage effect, driven primarily by capillary suction and osmosis. It depends on the microstructural characteristics of the substrate concrete, and may draw water and cement particles in suspension in the repair mixture into the concrete surface porosity. Absorption is strongly influenced by the moisture condition of the substrate concrete surface. A dry surface, depending on its absorption capabilities, tends to "suck" water from the repair material mixture. This can have both a negative or positive effect on the bond strength, depending on the absorption properties of the concrete substrate and amount of available moisture in the repair material mixture at the repair-substrate interface.

Conversely, adsorption processes, which result from the physical properties of the substrate at the microstructural level, may prevent water from moving into the substrate concrete.

Analysis of the laboratory and field test results yielded in the project and summarized in Table 11 reveals that in the case of dense high strength concrete overlaid with a cementitious repair material under controlled conditions, the extent of water conditioning of the substrate did not have much effect on the resulting repair bond strength.

This can lead to the conclusion that when moderate to high strength (equal to or greater than about 5000 psi) normal weight concrete substrates are repaired with ordinary concrete mixtures, the adsorption processes are likely to govern the water mass transport. In such cases, the moisture condition of the substrate surface does not affect significantly the bond strength developing between the two adjoined materials.

At the same time, for the low-strength (3000 psi) substrate concrete (test slabs MC-3-XX-CON), pre-wetting led to improved bond strength of the repair materials. The lower strength materials are characterized by a more porous and less dense binding phase (paste), so the absorption process prevailed over adsorption. Ponding of the concrete substrate for one hour increased the resulting bond strength by more than 12 % (231 to 264 psi), and the six-hour long ponding resulted in an increase of almost 30 % (231 to 324 psi).

Another important finding is related to the shrinkage of repair materials. Portland cement-based repair materials are subject to shrinkage as they cure and age. The results generated during the laboratory phase of the study demonstrate that when shrinkage stresses are minimized by using repair/overlay materials containing shrinkage-reducing admixtures and /or shrinkage-compensating component, such as the mortar used in the laboratory experiments (*Zero C*©, an extended mortar then produced by BASF), higher bond strength values are achieved as compared to those obtained with ordinary concrete mixtures, regardless of the extent of moisture conditioning of the concrete substrate.

This is likely the result of the effects of shrinkage of the repair mortar and the stress that causes at the repair/substrate interface. The 28-day drying shrinkage (as measured with ASTM C157, modified per ACI C364.3-09) of ordinary concrete mixtures typically reaches a value of the order of 0.05% and higher. Such a magnitude of drying shrinkage produces tensile stresses in the repair at the interface, which negatively affect the bond strength. In addition of the beneficial effect of reduced shrinkage, the early expansion occurring in a shrinkage-compensating repair system produces an early chemical pre-stress which has been found to promote enhanced bond strength (Certain *et al*., 2012).

An important finding from the field trials (test slabs made with 5000 psi and 7000 psi ready-mixed concrete mixtures) was that the best bond strength results – either short-term or long-term – were obtained without any moisture conditioning. While this probably indicates that a well prepared good quality concrete substrate may generally suffice to get optimal adhesion (without any wetting), further appraisal of these results is warranted. As stated before the test slabs used in the field were not aged for an extended period of time (8 months) and that during curing and conditioning they were exposed to winter conditions and a particularly wet spring season in Denver in 2015. As a result, the actual moisture levels recorded in the test slabs (Table 4) were significantly higher than those of the test slabs used in the laboratory program (Bissonnette, Vaysburd, & von Fay, 2013).

Nonetheless, what this may mean is that for Reclamation concrete structures that are de-watered prior to concrete repair, as long as the substrate concrete is of reasonably decent quality, no moisture conditioning is required in normal exposure conditions. This is consistent with the results yielded in a few other in-depth studies (Pigeon & Saucier, 1992; Bissonnette *et al*., 2016).

Finally, the field studies did not reveal any significant change in bond strength between the short-term test results and the test results determined at one-year. Seemingly, the 12-month exposure period in outdoor conditions did not lead to much further hydration of the interface nor to any significant distress, for any of the investigated test combinations. In other words, the 28-day bond strength test results may be fully indicative of future performance in most cases, at least in the cases where the interfacial bond strength exceeds the tensile strength of the substrate.

Obviously, one important consideration when dealing with the influence of concrete moisture upon repair bond is the ability to evaluate the actual concrete moisture in the field. Overall, the two measuring devices investigated in the present study were found to be effective and convenient. Embedded RH probes (*Rapid RH*®, manufactured by Wagner Meters, were used in the reported study) are useful and affordable tools for monitoring the relative humidity within the concrete cover (± 2 in.) over extended periods. Together with length change measurements, it can be used effectively to determine when (relatively) stable hygrometric conditions are achieved in a concrete member. Electrical impedance devices such as the *Moisture Encounter*™ (manufactured by Tramex) used in the research program can be used to determine when the concrete substrate surface has dried out sufficiently for concrete placement after pre-wetting. It should be considered as a viable alternative to more cumbersome and subjective methods in future revisions of the forthcoming ACI 364 *Technote* devoted to the determination of surface moisture condition of concrete surface prior to placement of repair material. Obviously, such meters require some calibration, which could be achieved on-site with a relatively light procedure, but determination of adequate moisture condition after pre-wetting would be greatly simplified and accelerated.

Table 5. – Pull-off Test Result Summary: Slab MC-5-0-CON5

		Short-term tests (2 months)			
		Total	**Repair failure**	**Interface failure**	**Substrate failure**
Avg. pull-off load (std. dev.)	**[lb]**	**1569** (195)	- -	1678 (124)	1544 (203)
Avg. pull-off load (std. dev.)	**[kN]**	**7.0** (0.9)	- -	7.5 (0.6)	6.9 (0.9)
Avg. bond strength (std. dev.)	**[psi]**	**270.5** (33.6)	- -	289.6 (22.4)	266.2 (34.9)
Avg. bond strength (std. dev.)	**[MPa]**	**1.87** (0.23)	- -	2.00 (0.15)	1.84 (0.24)
Bond strength COV	**[%]**	**12.4**	-	7.7	13.1
Intended no. of tests (cores)		16			
No. of valid tests		16			
Count (no. test results)	**[%]**	**16**	0	3	13
Relative count	**%**	100.0	0.0	18.8	81.3

		Long-term tests (1 year)			
		Total	**Repair failure**	**Interface failure**	**Substrate failure**
Avg. pull-off load (std. dev.)	**[lb]**	**1503** (185)	- -	1011 -	1522 (160)
Avg. pull-off load (std. dev.)	**[kN]**	**6.7** (0.8)	- -	4.5 -	6.8 (0.7)
Avg. bond strength (std. dev.)	**[psi]**	**256.5** (31.7)	- -	172.1 -	259.8 (27.4)
Avg. bond strength (std. dev.)	**[MPa]**	**1.77** (0.22)	- -	1.19 -	1.79 (0.19)
Bond strength COV	**[%]**	**12.4**	-	-	10.5
Intended no. of tests (cores)		31			
No. of valid tests		27			
Count (no. test results)	**[%]**	**27**	0	1	26
Relative count	**%**	100.0	0.0	3.7	96.3

Table 6. – Pull-off Test Result Summary: Slab MC-5-1-CON5

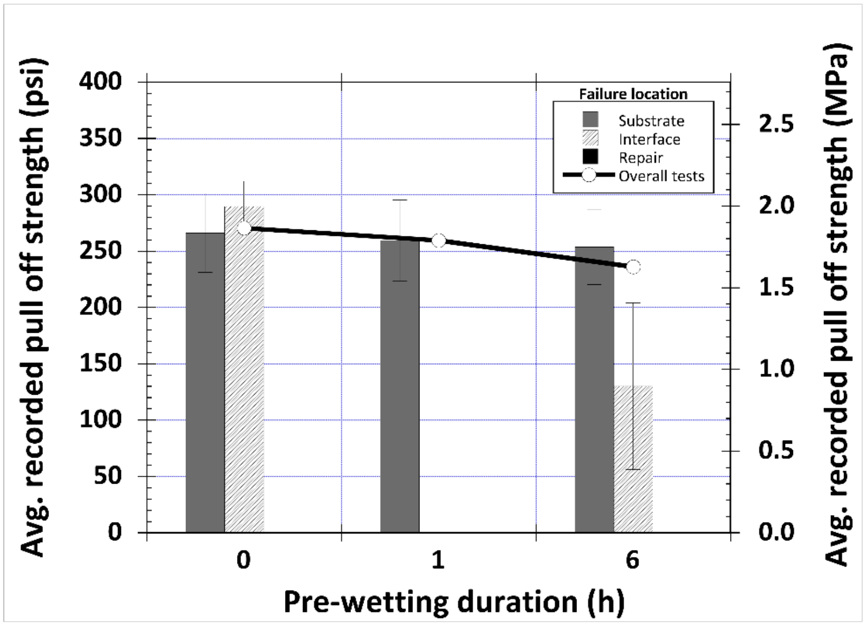
		Short-term tests (2 months)			
		Total	**Repair failure**	**Interface failure**	**Substrate failure**
Avg. pull-off load (std. dev.)	**[lb]**	**1506** (211)	- -	- -	1506 (211)
Avg. pull-off load (std. dev.)	**[kN]**	**6.7** (0.9)	- -	- -	6.7 (0.9)
Avg. bond strength (std. dev.)	**[psi]**	**259.4** (36.1)	- -	- -	259.4 (36.1)
Avg. bond strength (std. dev.)	**[MPa]**	**1.79** (0.25)	- -	- -	1.79 (0.25)
Bond strength COV	**[%]**	**13.9**	-	-	13.9
Intended no. of tests (cores)		15			
No. of valid tests		13			
Count (no. test results)	**[%]**	**13**	0	0	13
Relative count	**%**	100.0	0.0	0.0	100.0

		Long-term tests (1 year)			
		Total	**Repair failure**	**Interface failure**	**Substrate failure**
Avg. pull-off load (std. dev.)	**[lb]**	**1473** (292)	- -	360 -	1517 (188)
Avg. pull-off load (std. dev.)	**[kN]**	**6.6** (1.3)	- -	1.6 -	6.8 (0.8)
Avg. bond strength (std. dev.)	**[psi]**	**251.8** (49.9)	- -	62.3 -	259.4 (32.2)
Avg. bond strength (std. dev.)	**[MPa]**	**1.74** (0.34)	- -	0.43 -	1.79 (0.22)
Bond strength COV	**[%]**	**19.8**	-	-	12.4
Intended no. of tests (cores)		27			
No. of valid tests		26			
Count (no. test results)	**[%]**	**26**	0	1	25
Relative count	**%**	100.0	0.0	3.8	96.2

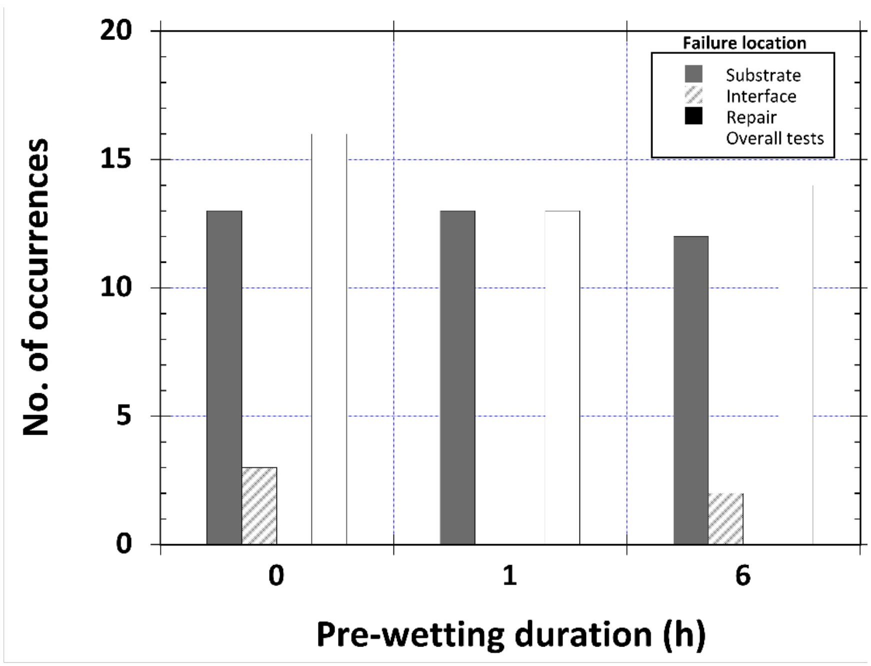
Table 7. – Pull-off Test Result Summary: Slab MC-5-6-CON5

		Short-term tests (2 months)			
		Total	Repair failure	Interface failure	Substrate failure
Avg. pull-off load (std. dev.)	[lb]	**1397** (333)	- -	753 (429)	1504 (162)
Avg. pull-off load (std. dev.)	[kN]	**6.2** (1.5)	- -	3.4 (1.9)	6.7 (0.7)
Avg. bond strength (std. dev.)	[psi]	**236.1** (58.1)	- -	130.2 (73.9)	253.8 (33.4)
Avg. bond strength (std. dev.)	[MPa]	**1.63** (0.40)	- -	0.90 (0.51)	1.75 (0.23)
Bond strength COV	[%]	**24.6**	-	56.8	13.1
Intended no. of tests (cores)		16			
No. of valid tests		14			
Count (no. test results)	[%]	**14**	0	2	12
Relative count	%	100.0	0.0	14.3	85.7

		Long-term tests (1 year)			
		Total	Repair failure	Interface failure	Substrate failure
Avg. pull-off load (std. dev.)	[lb]	**1427** (375)	- -	1146 (196)	4731 (12058)
Avg. pull-off load (std. dev.)	[kN]	**6.4** (1.7)	- -	5.1 (0.9)	21.1 (53.7)
Avg. bond strength (std. dev.)	[psi]	**244.7** (64.1)	- -	197.0 (33.8)	250.9 (64.9)
Avg. bond strength (std. dev.)	[MPa]	**1.69** (0.44)	- -	1.36 (0.23)	1.73 (0.45)
Bond strength COV	[%]	**26.2**	-	17.2	25.9
Intended no. of tests (cores)		30			
No. of valid tests		26			
Count (no. test results)	[%]	**26**	0	3	23
Relative count	%	100.0	0.0	11.5	88.5

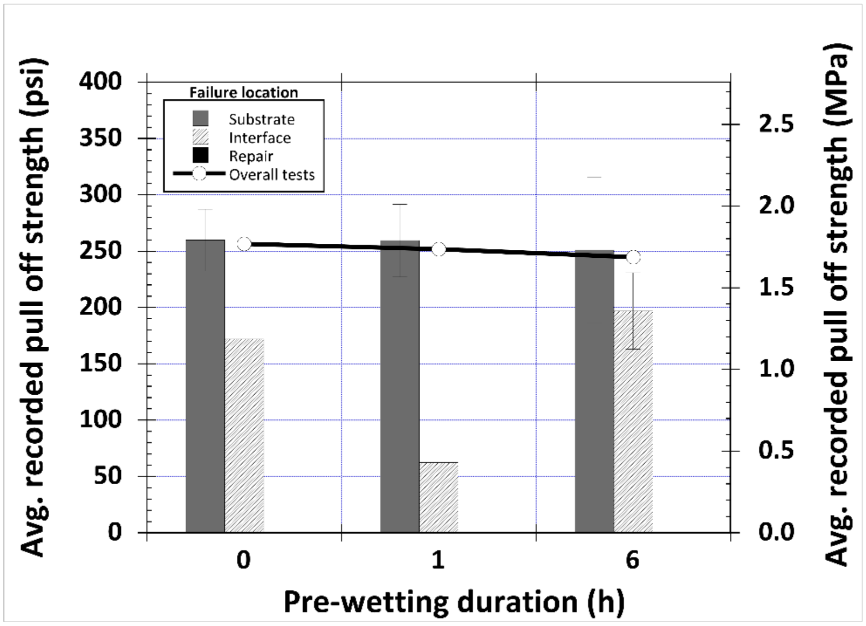


a) Bond strength results as a function of the failure location

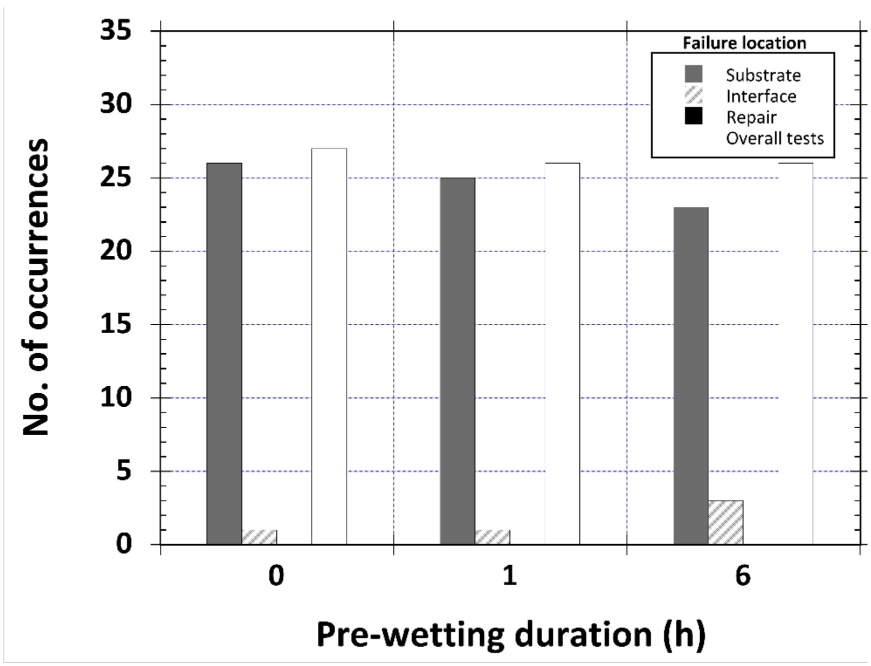


b) Failure location distribution

Figure 4. – Short-term (2 months) pull-off test results for slabs repaired with the 5000 psi concrete (MC-5-YY-CON5).



a) Bond strength results as a function of the failure location



b) Failure location distribution

Figure 5. – Long-term (1 year) pull-off test results for slabs repaired with the 5000 psi concrete (MC-5-YY-CON5).

Table 8. – Pull-off Test Result Summary: Slab MC-5-0-CON7

		Short-term tests (2 months)			
		Total	**Repair failure**	**Interface failure**	**Substrate failure**
Avg. pull-off load (std. dev.)	**[lb]**	**1509** (244)	- -	1360 (79)	1526 (252)
Avg. pull-off load (std. dev.)	**[kN]**	**6.7** (1.1)	- -	6.1 (0.4)	6.8 (1.1)
Avg. bond strength (std. dev.)	**[psi]**	**260.6** (42.3)	- -	234.3 (13.2)	263.5 (43.5)
Avg. bond strength (std. dev.)	**[MPa]**	**1.80** (0.29)	- -	1.62 (0.09)	1.82 (0.30)
Bond strength COV	**[%]**	**16.2**	-	5.6	16.5
Intended no. of tests (cores)		23			
No. of valid tests		20			
Count (no. test results)	**[%]**	**20**	0	2	18
Relative count	**%**	100.0	0.0	10.0	90.0

		Long-term tests (1 year)			
		Total	**Repair failure**	**Interface failure**	**Substrate failure**
Avg. pull-off load (std. dev.)	**[lb]**	**1668** (283)	- -	- -	1644 (265)
Avg. pull-off load (std. dev.)	**[kN]**	**7.4** (1.3)	- -	- -	7.3 (1.2)
Avg. bond strength (std. dev.)	**[psi]**	**280.3** (45.5)	- -	- -	280.3 (45.5)
Avg. bond strength (std. dev.)	**[MPa]**	**1.93** (0.31)	- -	- -	1.93 (0.31)
Bond strength COV	**[%]**	**16.2**	-	-	16.2
Intended no. of tests (cores)		25			
No. of valid tests		23			
Count (no. test results)	**[%]**	**23**	0	0	23
Relative count	**%**	100.0	0.0	0.0	100.0

Table 9. – Pull-off Test Result Summary: Slab MC-5-1-CON7

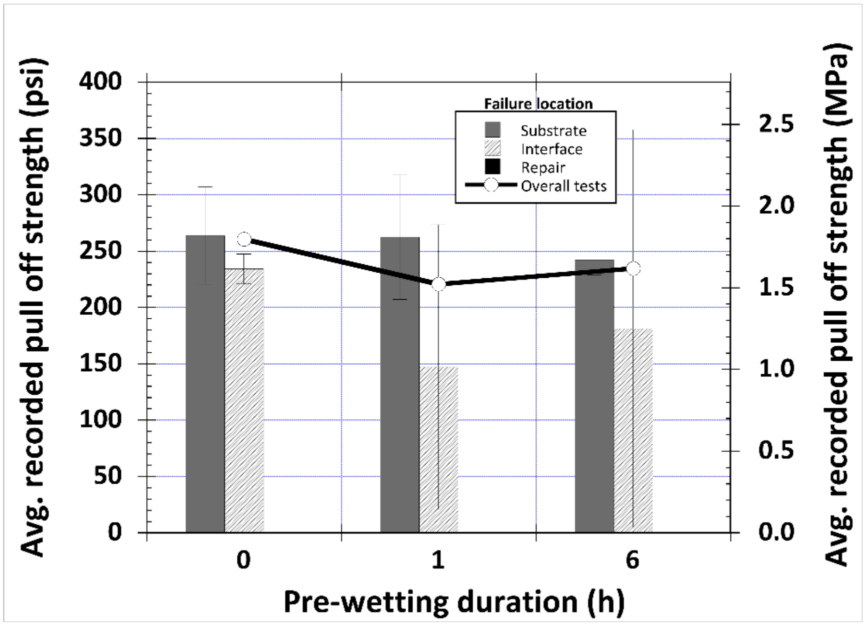
		Short-term tests (2 months)			
		Total	**Repair failure**	**Interface failure**	**Substrate failure**
Avg. pull-off load	**[lb]**	**1279**	-	854	1522
(std. dev.)		(582)	-	(732)	(326)
Avg. pull-off load	**[kN]**	**5.7**	-	3.8	6.8
(std. dev.)		(2.6)	-	(3.3)	(1.5)
Avg. bond strength	**[psi]**	**220.6**	-	147.2	262.5
(std. dev.)		(100.0)	-	(126.3)	(55.3)
Avg. bond strength	**[MPa]**	**1.52**	-	1.02	1.81
(std. dev.)		(0.69)	-	(0.87)	(0.38)
Bond strength COV	**[%]**	**45.3**	-	85.8	21.1
Intended no. of tests (cores)		15			
No. of valid tests		11			
Count (no. test results)	**[%]**	**11**	0	4	7
Relative count	**%**	100.0	0.0	36.4	63.6

		Long-term tests (1 year)			
		Total	**Repair failure**	**Interface failure**	**Substrate failure**
Avg. pull-off load	**[lb]**	**1457**	-	461	1540
(std. dev.)		(353)	-	(207)	(199)
Avg. pull-off load	**[kN]**	**6.5**	-	2.1	6.9
(std. dev.)		(1.6)	-	(0.9)	(0.9)
Avg. bond strength	**[psi]**	**248.3**	-	78.8	262.4
(std. dev.)		(60.0)	-	(35.3)	(34.0)
Avg. bond strength	**[MPa]**	**1.71**	-	0.54	1.81
(std. dev.)		(0.41)	-	(0.24)	(0.23)
Bond strength COV	**[%]**	**24.2**	-	44.8	12.9
Intended no. of tests (cores)		31			
No. of valid tests		26			
Count (no. test results)	**[%]**	**26**	0	2	24
Relative count	**%**	100.0	0.0	7.7	92.3

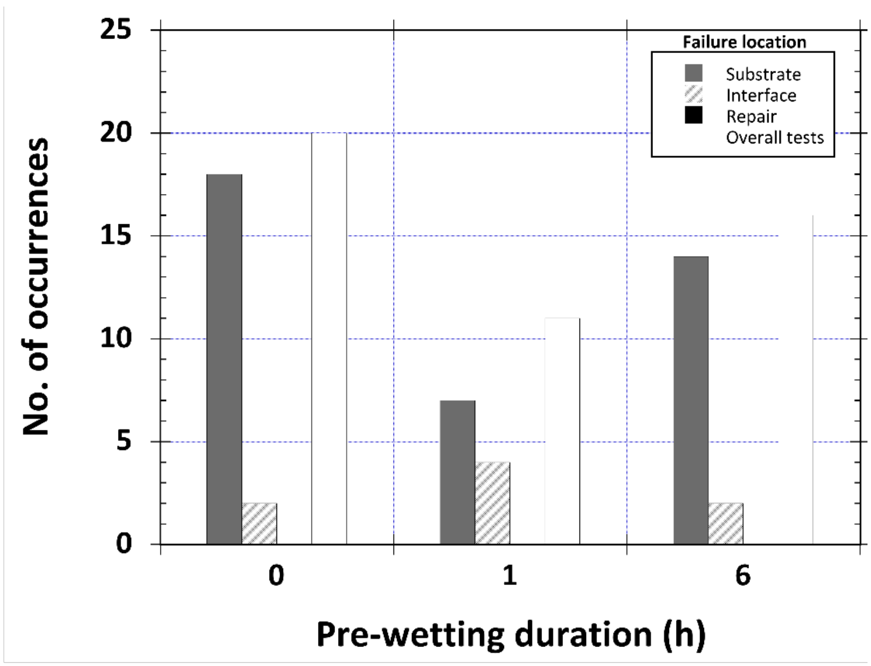
Table 10. – Pull-off Test Result Summary: Slab MC-5-6-CON7

		Short-term tests (2 months)			
		Total	**Repair failure**	**Interface failure**	**Substrate failure**
Avg. pull-off load	**[lb]**	**1591**	-	1225	1644
(std. dev.)		(350)	-	(1192)	(90)
Avg. pull-off load	**[kN]**	**7.1**	-	5.5	7.3
(std. dev.)		(1.6)	-	(5.3)	(0.4)
Avg. bond strength	**[psi]**	**234.6**	-	181.2	242.3
(std. dev.)		(51.6)	-	(176.5)	(13.3)
Avg. bond strength	**[MPa]**	**1.62**	-	1.25	1.67
(std. dev.)		(0.36)	-	(1.22)	(0.09)
Bond strength COV	**[%]**	**22.0**	-	97.4	5.5
Intended no. of tests (cores)		16			
No. of valid tests		16			
Count (no. test results)	**[%]**	**16**	0	2	14
Relative count	**%**	100.0	0.0	12.5	87.5

		Long-term tests (1 year)			
		Total	**Repair failure**	**Interface failure**	**Substrate failure**
Avg. pull-off load	**[lb]**	**1560**	-	1607	1556
(std. dev.)		(174)	-	(461)	(155)
Avg. pull-off load	**[kN]**	**6.9**	-	7.2	6.9
(std. dev.)		(0.8)	-	(2.1)	(0.7)
Avg. bond strength	**[psi]**	**266.8**	-	275.3	266.1
(std. dev.)		(30.0)	-	(79.1)	(26.6)
Avg. bond strength	**[MPa]**	**1.84**	-	1.90	1.84
(std. dev.)		(0.21)	-	(0.55)	(0.18)
Bond strength COV	**[%]**	**11.2**	-	28.7	10.0
Intended no. of tests (cores)		27			
No. of valid tests		27			
Count (no. test results)	**[%]**	**27**	0	2	25
Relative count	**%**	100.0	0.0	7.4	92.6

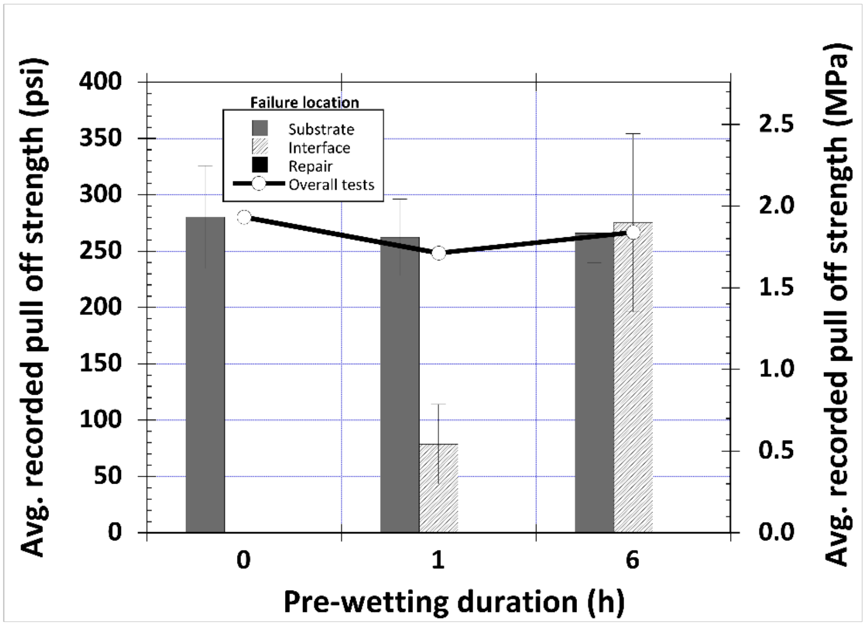


a) Bond strength results as a function of the failure location

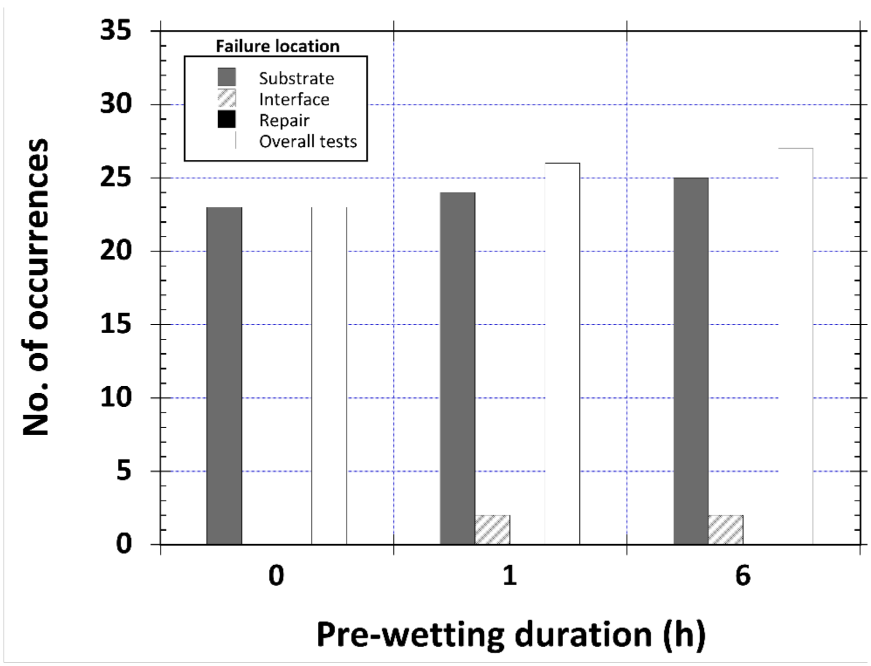


b) Failure location distribution

Figure 6. – Short-term (2 months) pull-off test results for slabs repaired with the 7000 psi concrete (MC-5-YY-CON7).



a) Bond strength results as a function of the failure location



b) Failure location distribution

Figure 7. – Long-term (1 year) pull-off test results for slabs repaired with the 7000 psi concrete (MC-5-YY-CON7).

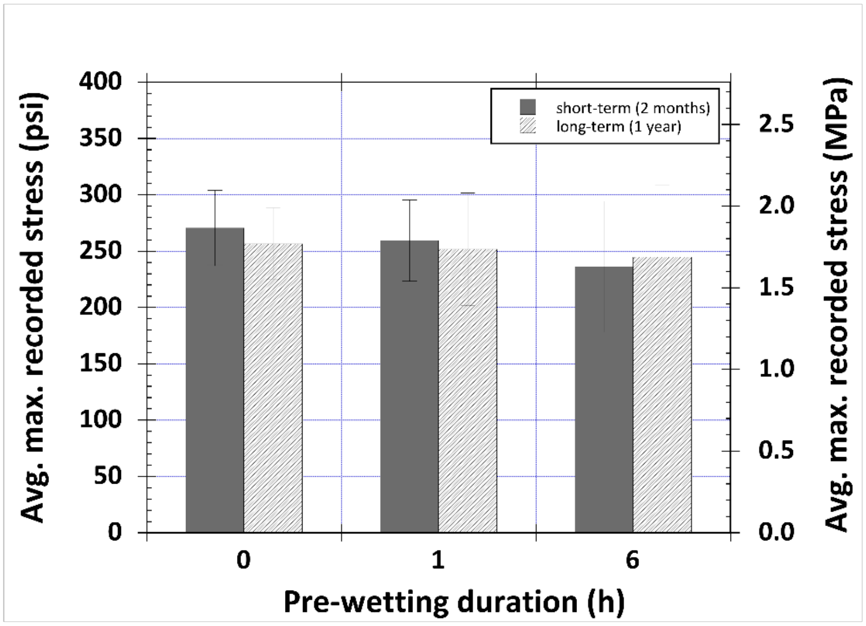


Figure 8. – Comparative pull-off test results for slabs repaired with the 5000 psi concrete (MC-5-YY-CON5).

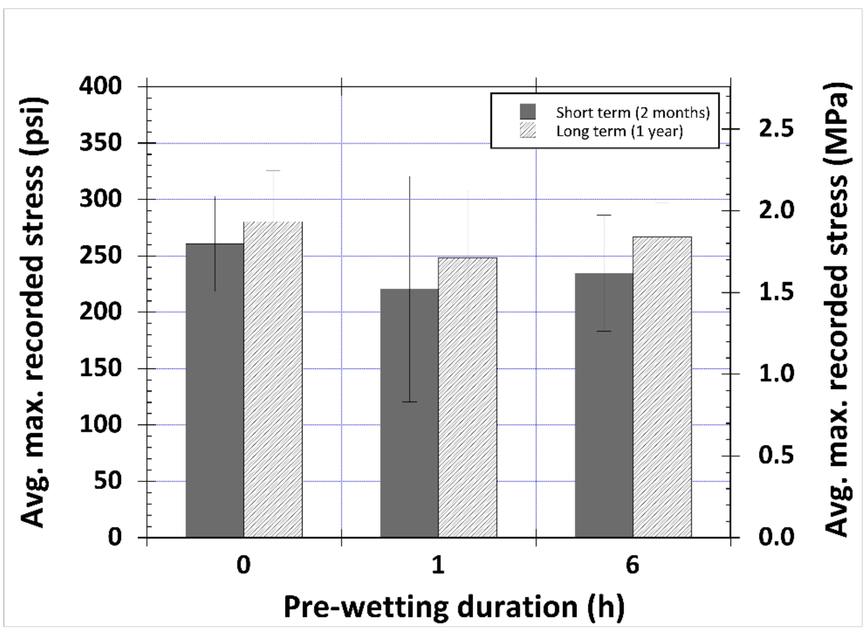


Figure 9. – Comparative pull-off test results for slabs repaired with the 7000 psi concrete (MC-5-YY-CON7).

Table 11. – Summary of the Laboratory and Field Test Results

Test slabs	Test result parameters		Age at testing	Pre-wetting duration		
				none	1 h	6 h
Laboratory test program						
MC-3-XX-CON	Avg. bond strength	[psi] [MPa]	2 months	230.7 1.59	263.5 1.82	324.3 2.24
	COV	[%]		25.9	19.0	7.8
MC-5-XX-CON	Avg. bond strength	[psi] [MPa]	2 months	268.1 1.85	280.8 1.94	282.6 1.95
	COV	[%]		42.0	27.5	23.5
MC-7-XX-CON	Avg. bond strength	[psi] [MPa]	2 months	281.5 1.94	262.7 1.81	267.1 1.84
	COV	[%]		48.7	47.2	43.5
MC-3-XX-BASF	Avg. bond strength	[psi] [MPa]	2 months	311.2 2.15	344.1 2.37	334.9 2.31
	COV	[%]		9.5	17.4	14.0
MC-5-XX-BASF	Avg. bond strength	[psi] [MPa]	2 months	422.8 2.92	420.7 2.90	352.9 2.43
	COV	[%]		10.7	11.1	7.7
MC-7-XX-BASF	Avg. bond strength	[psi] [MPa]	2 months	315.5 2.18	451.1 3.11	401.6 2.77
	COV	[%]		19.9	8.4	18.1
Field test program						
MC-5-XX-CON5	Avg. bond strength	[psi] [MPa]	2 months	270.5 1.87	259.4 1.79	236.1 1.63
	COV	[%]		12.4	13.9	24.6
MC-5-XX-CON5	Avg. bond strength	[psi] [MPa]	1 year	256.5 1.77	251.8 1.74	244.7 1.69
	COV	[%]		12.4	19.8	26.2
MC-5-XX-CON7	Avg. bond strength	[psi] [MPa]	2 months	260.6 1.80	220.6 1.52	234.6 1.62
	COV	[%]		16.2	45.3	22.0
MC-5-XX-CON7	Avg. bond strength	[psi] [MPa]	1 year	280.3 1.93	248.3 1.71	266.8 1.84
	COV	[%]		16.2	24.2	11.2

Conclusions

The following conclusions and recommendations resulted from this project.

1. When normal and higher strength (about 5000 psi and higher) concrete elements are being repaired or overlaid with portland cement-based materials, then for the conditions in this investigation, pre-wetting of the substrate is not necessary for optimum bond strength.
2. When lower strength concrete elements are being repaired or overlaid, the optimum bond strength is obtained with extended water ponding, such as the 6-hour period used in this project.
3. Repair or overlay material proportioned to be low-shrinkage (such as using shrinkage-compensating additives) under similar moisture conditioning of the concrete substrate results in higher bond strength when compared to ordinary concrete repair materials.
4. For the combination of materials and condition investigated in the field program of this study, the maximum bond strength was reached relatively early, within the first two months after the repair.
5. The conclusions developed from this study are based on very specific combinations of substrates and repair materials and moisture conditioning times. Further studies on different combinations of repair materials and substrate concretes, with a range of ageing and water conditioning, is recommended. Unfortunately, it is clear that there is no such thing as a single universal optimum moisture condition that would apply to any combination of repair materials and existing concrete substrate.
6. Guidelines and codes need to clearly define what the SSD conditions really mean in existing concrete and, where desirable, to provide guidance on how it can be achieved, depending on the actual substrate concrete characteristics and condition.
7. It is also recommended to investigate conditions under which the moisture transport mechanisms between the existing concrete and the repair material are driven by temperature gradients. Water tends to move within a porous medium from warmer areas to cooler ones and this may well influence the interfacial repair bond development, depending on the exposure conditions.
8. Embedded relative humidity probes can be used effectively for field monitoring of relative humidity at the surface of a concrete element and determination.
9. In view of assessing the substrate moisture condition proper for concrete placement after pre-wetting, electrical impedance meters provide a promising alternative or complementary option to other approaches proposed in the forthcoming ACI 364 *Technote*.

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Appendix 1

Photographs of Field Testing Operations

Figure 1. – One of the three 5 by 8 ft cast-in-place test slabs prepared for the field experiments at the Federal Center in December, 2014.

Figure 1. – Surface preparation of the test slabs by sandblasting.

Figure 2. – Surface texture of the test slab after sandblasting and embedded R.H. probe installed for monitoring of moisture inside concrete.

Figure 3. – Formwork installed on one of the cast-in-place 5 by 8 ft test slab prior to overlay placement.

Figure 4. – Mobile water tank used for slab ponding operation.

Figure 5. – Moisture conditioning (ponding) implemented on the test slabs prior to overlay placement.

Figure 6. – On-site ready-mix concrete delivery for overlay placement.

Figure 7. – Casting of overlays.

Figure 8. – Placement of repair/overlay concrete.

Figure 9. – Vibration of repair/overlay concrete.

Figure 10. – Surface finishing operation.

Figure 11. – Overlaid test slab after the finishing operation.

Figure 12. – Marking of the test slab surface for pull off testing.

Figure 13. – Core drilling operation.

Figure 14. – Pull off testing with the Germann Instruments equipment.

Figure 15. – Example of repair material failure in the pull off test.

Figure 16. – Example of interfacial failure in the pull off test.

Figure 17. – Example of substrate failure in the pull off test.

Figure 18. – Short-term pull off testing layout on test slab C (C1: MC-5-0-CON5; C2: MC-5-0-CON7).

Figure 19. – Short-term pull off testing layout on test slab B (B1: MC-5-1-CON5; B2: MC-5-1-CON7).

Figure 20. – Short-term pull off testing layout on test slab A (A1: MC-5-6-CON5; A2: MC-5-6-CON7).

Figure 21. – Long-term pull off testing layout on test slab C1 (MC-5-0-CON5).

Figure 22. – Long-term pull off testing layout on test slab C2 (MC-5-0-CON7).

Figure 23. – Long-term pull off testing layout on test slab B1 (MC-5-1-CON5).

Figure 24. – Long-term pull off testing layout on test slab B2 (MC-5-1-CON7).

Figure 25. – Long-term pull off testing layout on test slab A1 (MC-5-6-CON5).

Figure 26. – Long-term pull off testing layout on test slab A2 (MC-5-6-CON7).

Appendix 2

Pull off Test Results

Table 1. – Short-Term Pull Off Test Results: Slab MC-5-0-CON5 (t = 2 months)

Pull off bond strength - Slab MC-5-0-CON5 (short term)				
Core #	Bond strength (psi)	(MPa)	Failure mode (R / I / S)	Observations
1	320.7	2.21	substrate	
3	311.2	2.15	interface	
4	271.6	1.87	substrate	
6	307.7	2.12	substrate	
15	266.5	1.84	interface	
18	282.5	1.95	substrate	
19	255.9	1.77	substrate	
21	291.0	2.01	interface	
22	220.9	1.52	substrate	
24	264.2	1.82	substrate	
25	301.2	2.08	substrate	
28	194.2	1.34	substrate	
33	240.3	1.66	substrate	
36	275.6	1.90	substrate	
43	274.2	1.89	substrate	
46	251.0	1.73	substrate	
Average	**270.5**	**1.87**	**Repair (%)**	0.0
Std. Deviation	33.6	0.23	**Interface (%)**	18.8
COV (%)	12.4		**Substrate (%)**	81.3

Table 2. – Long-Term Pull Off Test Results: Slab MC-5-0-CON5 (t = 1 year)

Pull off bond strength - Slab MC-5-0-CON5 (long term)				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode (R / I / S)**	**Observations**
5			epoxy	epoxy
7	299.8	2.07	substrate	
8	257.1	1.77	substrate	
9	N/A	N/A	epoxy	epoxy
10	295.1	2.04	substrate	
11	256.7	1.77	substrate	
12	N/A	N/A	epoxy	epoxy
13	245.8	1.70	substrate	
14	276.8	1.91	substrate	
16	269.6	1.86	substrate	
17	306.7	2.12	substrate	
20	234.0	1.61	substrate	
23	295.0	2.03	substrate	
26	241.7	1.67	substrate	
27	291.0	2.01	substrate	
29	256.3	1.77	substrate	
30	261.3	1.80	substrate	
31	N/A	N/A	repair	coring too shallow (load = 15.3 kN)
32	230.5	1.59	substrate	
34	172.1	1.19	interface	
35	236.5	1.63	substrate	
37	276.1	1.90	substrate	
38	260.5	1.80	substrate	
39	237.9	1.64	substrate	
40	244.9	1.69	substrate	
41	269.7	1.86	substrate	
42	284.1	1.96	substrate	
44	283.8	1.96	substrate	
45	222.7	1.54	substrate	
47	210.3	1.45	substrate	
48	210.5	1.45	substrate	
Average	**256.5**	**1.77**	**Repair (%)**	0.0
Std. Deviation	31.7	0.22	**Interface (%)**	3.7
COV (%)	12.4		**Substrate (%)**	96.3

Table 3. – Short-Term Pull Off Test Results: Slab MC-5-1-CON5 (t = 2 months)

Pull off bond strength - Slab MC-5-1-CON5 (short term)				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode (R / I / S)**	**Observations**
1	268.1	1.85	substrate	
3	267.3	1.84	substrate	
4	147.8	1.02	substrate	
6	279.9	1.93	substrate	
19	247.5	1.71	substrate	
21	255.8	1.76	substrate	
22	270.4	1.87	substrate	
25	266.4	1.84	substrate	
27	278.8	1.92	substrate	
28	286.0	1.97	substrate	
30	N/A	N/A	epoxy/repair	failure in the epoxy layer
43	289.0	1.99	substrate	
45	244.2	1.68	substrate	
46	270.8	1.87	substrate	
48	N/A	N/A	epoxy	failure in the epoxy layer
Average	**259.4**	**1.79**	**Repair (%)**	0.0
Std. Deviation	36.1	0.25	**Interface (%)**	0.0
COV (%)	13.9		**Substrate (%)**	100.0

Table 4. – Long-Term Pull Off Test Results: Slab MC-5-1-CON5 (t = 1 year)

Pull off bond strength - Slab MC-5-1-CON5 (long term)				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode (R / I / S)**	**Observations**
9	225.6	1.56	substrate	
12	255.1	1.76	substrate	
13	245.7	1.69	substrate	initial mm glue problem (test repeated)
14	263.6	1.82	substrate	
15	261.8	1.81	substrate	
16	196.2	1.35	substrate	
17	211.7	1.46	substrate	
18	264.9	1.83	substrate	initial mm glue problem (test repeated)
20	231.1	1.59	substrate	initial mm glue problem (test repeated)
23	245.8	1.70	substrate	
24	N/A	N/A	coring too shallow	coring too shallow
26	268.9	1.85	substrate	
29	265.1	1.83	epoxy/substrate	initial mm glue problem (test repeated)
31	279.4	1.93	substrate	
32	276.4	1.91	substrate	
33	62.3	0.43	interface	
34	284.3	1.96	substrate	initial mm glue problem (test repeated)
35	226.0	1.56	substrate	
36	226.6	1.56	substrate	initial mm glue problem (test repeated)
37	342.3	2.36	substrate	
38	281.7	1.94	substrate	initial mm glue problem (test repeated)
39	292.7	2.02	substrate	initial mm glue problem (test repeated)
40	238.3	1.64	substrate	
41	249.0	1.72	N/A	initial mm glue problem (test repeated)
42	257.1	1.77	substrate	
44	315.6	2.18	substrate	
47	280.0	1.93	substrate	initial mm glue problem (test repeated)
Average	**251.8**	**1.74**	**Repair (%)**	0.0
Std. Deviation	49.9	0.34	**Interface (%)**	3.8
COV (%)	19.8		**Substrate (%)**	96.2

Table 5. – Short-Term Pull Off Test Results: Slab MC-5-6-CON5 (t = 2 months)

Pull off bond strength - Slab MC-5-6-CON5 (short term)				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode (R / I / S)**	**Observations**
3	217.1	1.50	substrate	
6	182.4	1.26	interface	
9	225.4	1.55	substrate	
13	255.6	1.76	substrate	
16	221.2	1.53	substrate	
25	291.5	2.01	substrate	
26	N/A	N/A	N/A	
27	202.2	1.39	substrate	
28	294.6	2.03	substrate	
30	233.1	1.61	substrate	
31	272.1	1.88	substrate	
34	300.0	2.07	substrate	
44	N/A	N/A	N/A	coring not deep enough
45	261.0	1.80	substrate	
46	271.9	1.88	substrate	
48	77.9	0.54	substrate/interface	
Average	**236.1**	**1.63**	**Repair (%)**	0.0
Std. Deviation	58.1	0.40	**Interface (%)**	14.3
COV (%)	24.6		**Substrate (%)**	85.7

Table 6. – Long-term Pull Off Test Results: Slab MC-5-6-CON5 (t = 1 year)

Pull off bond strength - Slab MC-5-6-CON5 (long term)				
Core #	**Bond strength**		**Failure mode**	**Observations**
	(psi)	**(MPa)**	**(R / I / S)**	
1	209.5	1.45	substrate	
2	311.9	2.15	substrate	
4	274.5	1.89	substrate	
5	271.9	1.88	substrate	
7	230.4	1.59	substrate	
8	257.6	1.78	substrate	
11	338.3	2.33	substrate	
12	220.3	1.52	interface	
14	153.9	1.06	substrate	
15	266.0	1.83	substrate	
18	158.2	1.09	interface	
19	242.3	1.67	substrate	
20	273.5	1.89	substrate	
21	N/A	N/A	coring too shallow	
22	N/A	N/A	N/A	broke while coring
23	92.6	0.64	substrate	
24	212.4	1.46	interface	
29	253.9	1.75	substrate	
32	262.8	1.81	substrate	
33	296.6	2.05	substrate	
35	N/A	N/A	substrate	damaged while coring (load = 0.6 kN)
36	319.5	2.20	substrate	
37	N/A	N/A	N/A	broke while coring
38	289.5	2.00	substrate	
39	257.7	1.78	substrate	
40	234.6	1.62	substrate	
41	281.4	1.94	substrate	
42	270.7	1.87	substrate	
43	304.2	2.10	substrate	
48	77.9	0.54	substrate/interface	
Average	**244.7**	**1.69**	**Repair (%)**	0.0
Std. Deviation	64.1	0.44	**Interface (%)**	11.5
COV (%)	26.2		**Substrate (%)**	88.5

Table 7. – Short-Term Pull Off Test Results: Slab MC-5-0-CON7 (t = 2 months)

Pull off bond strength - Slab MC-5-0-CON7 (short term)				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode (R / I / S)**	**Observations**
1	244.5	1.69	substrate	
3	338.3	2.33	substrate	
6	290.1	2.00	substrate	
13	228.7	1.58	substrate	
15	241.6	1.67	substrate	
16	302.9	2.09	substrate	
18	N/A	N/A	N/A	coring not deep enough
19	283.3	1.95	substrate	
21	178.0	1.23	substrate	
22	248.2	1.71	substrate	
24	225.0	1.55	interface	
25	263.6	1.82	substrate	
27	N/A	N/A	N/A	broke while coring
28	209.9	1.45	substrate	
30	N/A	N/A	N/A	coring not deep enough
31	268.0	1.85	substrate	
33	235.7	1.63	substrate	
34	299.2	2.06	substrate	
36	307.0	2.12	substrate	
43	221.5	1.53	substrate	
45	243.7	1.68	interface	
46	245.1	1.69	substrate	
48	337.3	2.33	substrate	
Average	**260.6**	**1.80**	**Repair (%)**	0.0
Std. Deviation	42.3	0.29	**Interface (%)**	10.0
COV (%)	16.2		**Substrate (%)**	90.0

Table 8. – Long-Term Pull Off Test Results: Slab MC-5-0-CON7 (t = 1 year)

Pull off bond strength - Slab MC-5-0-CON7 (long term)				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode (R / I / S)**	**Observations**
2	318.6	2.20	substrate	
4	336.4	2.32	substrate	
5	361.4	2.49	substrate	
7	376.2	2.59	substrate	
8	273.2	1.88	substrate	
9	272.1	1.88	substrate	
10	307.1	2.12	substrate	
11	307.1	2.12	substrate	
12	338.3	2.33	substrate	
14	305.4	2.11	substrate	
17	283.8	1.96	substrate	
20	N/A	N/A	N/A	broke while coring
23	259.5	1.79	substrate	
26	183.6	1.27	substrate	
29	260.1	1.79	substrate	
32	257.2	1.77	substrate	
35	242.1	1.67	substrate	
37	251.6	1.74	substrate	
38	267.2	1.84	substrate	
39	240.6	1.66	substrate	
40	248.0	1.71	substrate	
41	241.3	1.66	substrate	
42	N/A	N/A	repair	coring too shallow
44	282.5	1.95	substrate	
47	233.3	1.61	substrate	
Average	**280.3**	**1.93**	**Repair (%)**	0.0
Std. Deviation	45.5	0.31	**Interface (%)**	0.0
COV (%)	16.2		**Substrate (%)**	100.0

Table 9. – Short-Term Pull Off Test Results: Slab MC-5-1-CON7 (t = 2 months)

Pull off bond strength - Slab MC-5-1-CON7 (short term)				
Core #	Bond strength (psi)	(MPa)	Failure mode (R / I / S)	Observations
1	N/A	N/A	N/A	broke while coring
3	N/A	N/A	N/A	broke while coring
4	50.3	0.35	interface	
6	27.1	0.19	interface	
13	N/A	N/A	N/A	broke while coring
16	240.2	1.66	interface	
21	271.1	1.87	interface	
24	207.2	1.43	substrate	
27	240.5	1.66	substrate	
30	213.5	1.47	substrate	
34	249.9	1.72	substrate	
43	N/A	N/A	N/A	broke while coring
45	274.0	1.89	substrate	
46	370.7	2.56	substrate	
48	281.8	1.94	substrate	
Average	**220.6**	**1.52**	**Repair (%)**	0.0
Std. Deviation	100.0	0.69	**Interface (%)**	36.4
COV (%)	45.3		**Substrate (%)**	63.6

Table 10. – Long-Term Pull Off Test Results: Slab MC-5-1-CON7 (t = 1 year)

Pull off bond strength - Slab MC-5-1-CON7 (long term)				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode (R / I / S)**	**Observations**
2	N/A	N/A	N/A	broke while coring
5	264.5	1.82	substrate	
8	N/A	N/A	N/A	broke while coring
9	N/A	N/A	N/A	broke while coring
10	277.9	1.92	substrate	
11	259.8	1.79	substrate	
12	258.4	1.78	substrate	
14	326.3	2.25	substrate	
15	271.8	1.87	substrate	
17	258.7	1.78	substrate	
18	286.5	1.98	substrate	
19	N/A	N/A	N/A	broke while coring
20	264.6	1.83	substrate	
22	306.7	2.12	substrate	
23	265.4	1.83	substrate	
25	53.8	0.37	interface	
26	244.5	1.69	substrate	
28	299.8	2.07	substrate	
29	184.8	1.27	substrate	
32	194.9	1.34	substrate	
33	257.2	1.77	substrate	
35	184.0	1.27	substrate	
36	276.5	1.91	substrate	
37	N/A	N/A	N/A	broke while coring
38	265.2	1.83	substrate	
39	260.4	1.80	substrate	
40	282.6	1.95	substrate	
41	263.7	1.82	N/A	
42	282.7	1.95	substrate	
44	103.8	0.72	interface	
47	260.4	1.80	substrate	
Average	**248.3**	**1.71**	**Repair (%)**	0.0
Std. Deviation	60.0	0.41	**Interface (%)**	7.7
COV (%)	24.2		**Substrate (%)**	92.3

Table 11. – Short-Term Pull Off Test Results: Slab MC-5-6-CON7 (t = 2 months)

Pull off bond strength - Slab MC-5-6-CON7 (short term)				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode (R / I / S)**	**Observations**
3	225.5	1.56	substrate	
6	244.7	1.69	substrate	
14	261.7	1.80	substrate	
16	245.1	1.69	substrate	
19	215.2	1.48	substrate	
21	241.5	1.67	substrate	
23	241.6	1.67	substrate	
24	258.9	1.79	substrate	
25	56.3	0.39	interface	
27	235.1	1.62	substrate	
29	242.3	1.67	substrate	
30	225.1	1.55	substrate	
32	248.9	1.72	substrate	
34	254.8	1.76	substrate	
45	251.2	1.73	substrate	
48	306.0	2.11	substrate/interface	
Average	**234.6**	**1.62**	**Repair (%)**	0.0
Std. Deviation	51.6	0.36	**Interface (%)**	12.5
COV (%)	22.0		**Substrate (%)**	87.5

Table 12. – Long-Term Pull Off Test Results: Slab MC-5-6-CON7 (t = 1 year)

Pull off bond strength - Slab MC-5-6-CON7 (long term)				
Core #	**Bond strength (psi)**	**(MPa)**	**Failure mode (R / I / S)**	**Observations**
1	261.0	1.80	substrate	
2	223.7	1.54	substrate	
4	329.0	2.27	substrate	
5	300.3	2.07	substrate	
10	227.1	1.57	substrate	
13	281.1	1.94	substrate	
15	296.3	2.04	substrate	
17	242.5	1.67	substrate	
18	265.6	1.83	substrate	
20	238.6	1.65	substrate	
22	219.4	1.51	substrate/interface	interface failure
26	253.4	1.75	substrate	
28	281.2	1.94	substrate	
31	238.1	1.64	substrate	
33	274.8	1.90	substrate	
35	288.4	1.99	substrate	
36	292.4	2.02	substrate	
37	283.9	1.96	substrate	
38	242.0	1.67	substrate	
39	264.6	1.83	substrate	
40	294.2	2.03	substrate	
41	269.0	1.86	substrate	
42	263.7	1.82	substrate	
43	268.7	1.85	substrate	
44	242.9	1.68	substrate	
46	229.7	1.58	substrate	
47	331.3	2.28	substrate/interface	interface failure
Average	**266.8**	**1.84**	**Repair (%)**	0.0
Std. Deviation	30.0	0.21	**Interface (%)**	7.4
COV (%)	11.2		**Substrate (%)**	92.6