Concrete substrate moisture requirements for durable concrete repairs – a field study

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Abstract. In concrete repair specifications, the required moisture condition of the substrate, which can play an important role for bond development, and, ultimately, on the long-term repair / overlay durability, is generally ill-defined and addressed without due consideration to the given substrate characteristics. The standard specification, if any, is to require 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 founded on rational considerations, but it has never really been precisely defined, measured, nor validated. The influence of substrate surface moisture on the bond between the existing concrete and the new repair material is an issue of significant importance. This paper revisits the question, in light of results from a 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. Over the course of the project, multiple series of test slabs were repaired after being subjected to different surface moisture conditioning and then tested for bond strength tests at different ages. The findings are discussed, together with those from previous studies, and recommendations are issued.

1 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

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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. While it provides an intuitive solution to avoid problems, it 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 widely recognized by researchers and practitioners [1-4]. 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 has 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, 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) 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.

2 Objectives of the research

The ultimate objective of the research to which this paper relates is to develop guidance on how to determine the optimum concrete substrate moisture condition prior to applying a repair or overlay material, in order to maximize bond strength in the resulting composite system and achieve long lasting and durable repairs. The specific objectives 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 investigate field methods 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 these 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.

The work reported in this paper intended to evaluate the use of moisture measurement devices and study the influence of different moisture conditioning treatments in field experiments.

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. 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 [15] do not exhibit the same trends as often reported or described in the scientific documentation. 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 carry out only pull-off testing.

3 Field experiments

3.1 Description and methodology

Before undertaking the field test program, three (3) concrete test slabs-on-grade (1.5 m × 2.5 m) were cast at the Denver Federal Center (Denver, CO) using the basic 35-MPa BOR concrete mixture (ordinary portland cement with 20% of fly ash; w/cm = 0.39; 20-mm coarse agg.; fin/coarse agg. = 0.39) used in previous part of this study [6]. 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.

The test slabs were stored outside, under a canopy over the slabs to protect them from direct precipitation. Shrinkage and moisture content were monitored at the surface of the slabs throughout the conditioning period. After more than six months of conditioning, the slabs were lightly sandblasted for consistent and adequate roughness of the surfaces to be overlaid. 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 Bureau of Reclamation and Laval University [6-7], the selected criterion for the *SSD* condition was a threshold value of 3.5.

Two repair concrete mixtures were used in these field experiments:

- 35-MPa BOR ready-mix concrete delivered on site, with the exact same composition as the mixture used to cast the slabs;
- 50-MPa BOR ready-mix concrete delivered on site (ordinary portland cement with 20% of fly ash; w/cm = 0.30; 20-mm coarse agg.; fin/coarse agg. = 0.42).

Each test slab was overlaid on one half (1.5 by 1.25 m) with the 35-MPa concrete mixture, and on the other half with the 50-MPa concrete mixture. After overlaying, the slabs were moist cured for 7 days, covered with clear plastic, and then exposed to outdoor conditions under a canopy.

In the subsequent sections, each test slab subset is identified using the following identification key:

MC – X – Y – Z
where:
X (concrete slab strength, MPa): 20* – **35** – 50*
Y (pre-wetting time, h): **0** – **1** – **6**
Z (repair material type): **CON35 (35-MPa concrete)**
CON50 (50-MPa concrete)
EXM (extended mortar) *

* (*parameters tested in the laboratory phase only*)

For example, the MC-5-1-CON5 slab is a 35 MPa base slab that was ponded for 1 hour and repaired with the 50 MPa concrete. The same naming scheme will be used throughout this report.

Testing for tensile bond strength was carried out 2 months (short-term) and 1 year (long-term) after the repair. It should be mentioned that the core distribution between short-term and long-term pull-off testing in each half-slab was selected randomly. 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.

3.2 Moisture conditioning of the slabs prior to repair

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 1. 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.

The slabs tested in the field program were not aged for an extended period of time and given the fact that the 8-month conditioning they were subjected to coincided with the winter and 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. The bulk moisture content in the field test slabs was likely much higher than that of the slabs tested in the laboratory program.

a) b)

Fig. 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.

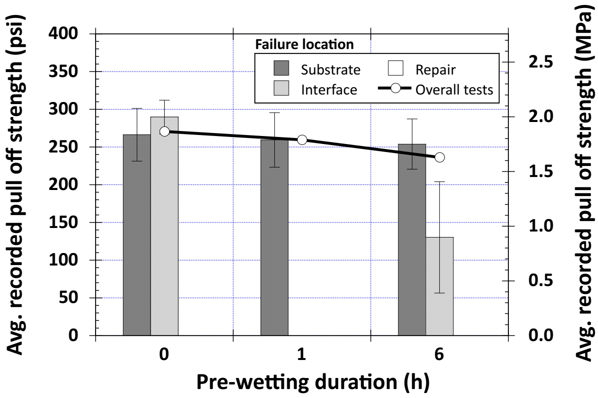
Just prior to repair, two of the three slabs were moist conditioned for 1 and 6 hours respectively. Moist conditioning was carried out by ponding. After the end of the ponding period, water was completely removed and the surface was exposed to air drying. Ready-mix trucks were ordered to arrive on site approximately 30 minutes after drying had begun. Based upon previous experiments at USBR 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. The results of the measurements performed prior to moisture conditioning, after ponding and at the time of repair placement are summarized in Table 1.

Table 1. Moisture conditioning test results.

Test slab ID	Superficial moisture condition Electrical Impedance Method (device reading units)		
	prior to moisture conditioning	after ponding	at time of repair placement
MC-35-0-CON35	2.5	-	2.5
MC-35-0-CON50	2.5	-	2.5
MC-35-1-CON35	3.2	3.7	3.5
MC-35-1-CON50	2.9	3.3	3.4
MC-35-6-CON35	2.9	3.6	3.4
MC-35-6-CON50	3.0	3.6	3.3

4 Test results and discussion

The main results field experiments carried out in this part of the research project are summarized in Figures 2 to 7. In general, excellent bond was achieved, with a low rate of failure occurrence away from the substrate.



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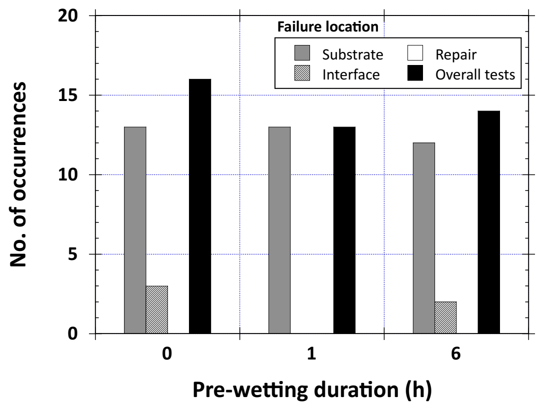

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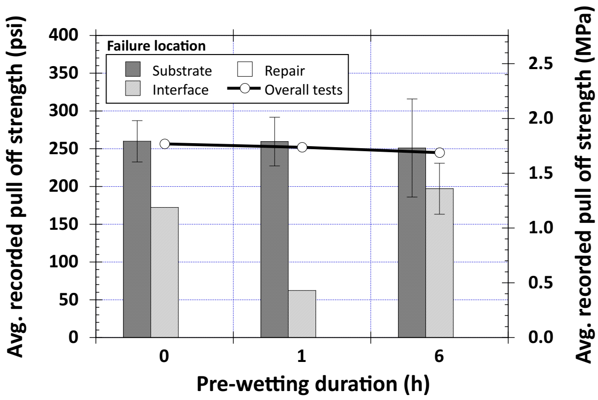
Fig. 2. Short-term (2 months) pull-off test results for slabs repaired with the 35-MPa concrete (MC-35-YY-CON35): a) bond strength results as a function of the failure location; b) failure location distribution.

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 it.

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.



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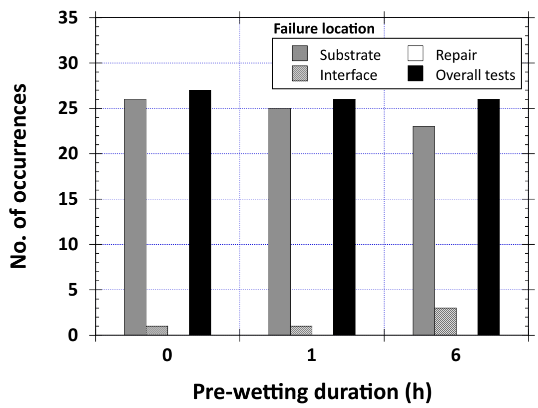

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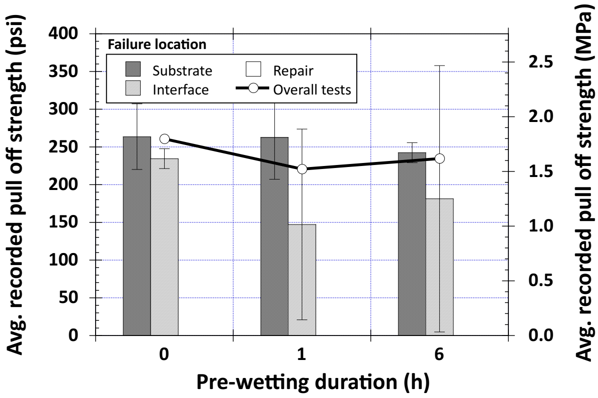
Fig. 3. Long-term (1 year) pull-off test results for slabs repaired with the 35-MPa concrete (MC-35-YY-CON35): a) bond strength results as a function of the failure location; b) failure location distribution.

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.

In Table 2, the bond test results yielded the field test program are summarized with the data generated previously in the laboratory experiments. Analysis of the results altogether reveals that in the case of dense high strength concrete mixtures 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 35 MPa) 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.



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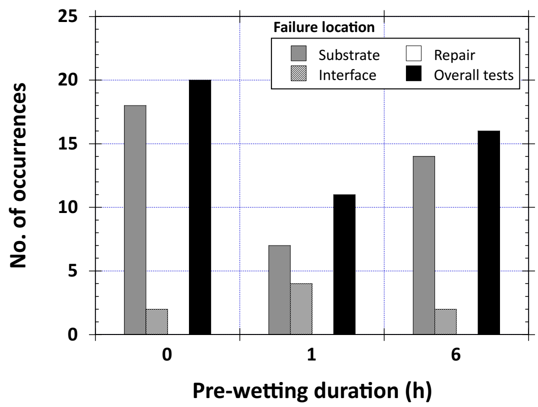

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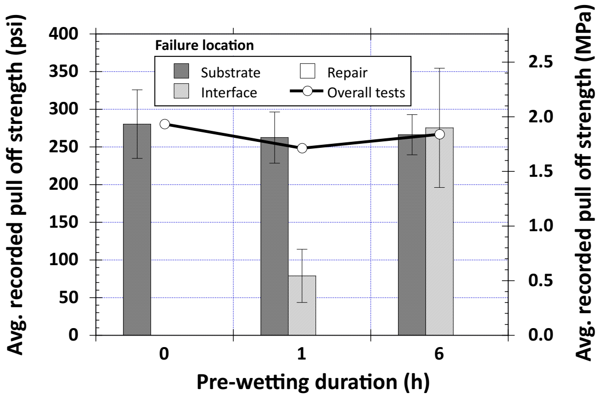
Fig. 4. Short-term (2 months) pull-off test results for slabs repaired with the 50-MPa concrete (MC-35-YY-CON50): a) bond strength results as a function of the failure location; b) failure location distribution.

At the same time, for the low-strength (20 MPa) 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% (1.59 to 1.82 MPa), and the six-hour long ponding resulted in an increase of almost 30% (1.59 to 2.23 MPa).

Another important finding is related to the shrinkage of repair materials. Portland cement-based repair materials are subject to shrinkage as they 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 (extended proprietary mortar), 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 [8], modified per ACI PRC-364.3 [9]) 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 is producing an early chemical pre-stress which has been found to promote enhanced bond strength [10].



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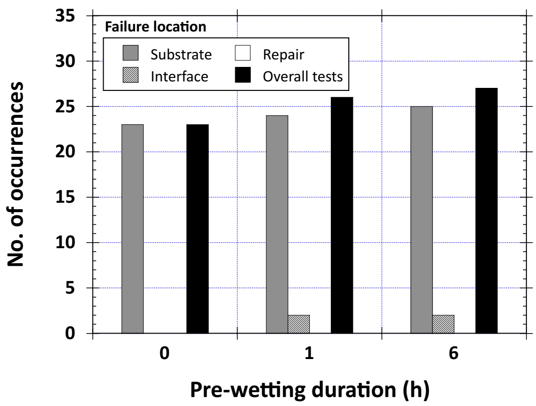

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Fig. 5. Long-term (1 year) pull-off test results for slabs repaired with the 50-MPa concrete (MC-35-YY-CON50): a) bond strength results as a function of the failure location; b) failure location distribution.

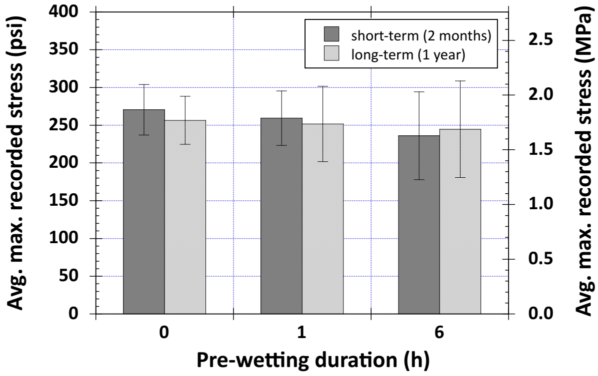

Fig. 6. Comparative pull-off test results for slabs repaired with the 35-MPa concrete (MC-35-YY-CON35).

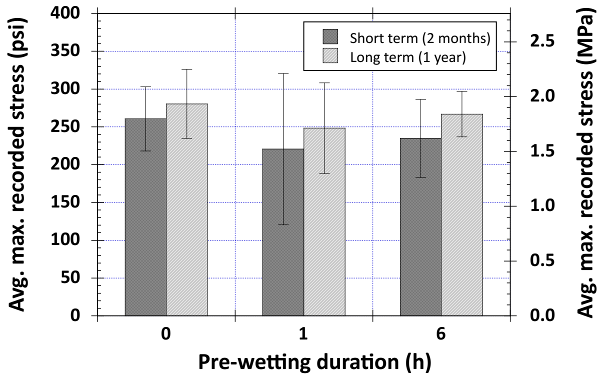

Fig. 7. Comparative pull-off test results for slabs repaired with the 50-MPa concrete (MC-35-YY-CON50).

An important finding from the field trials (test slabs made with 35 MPa and 50 MPa 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. 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 were significantly higher than those of the test slabs used in the laboratory program [6].

Nonetheless, what this may mean is that in many instances, as long as the substrate concrete is of reasonably decent quality, no moisture conditioning is actually required in normal exposure conditions. This is consistent with the results yielded in a few other in-depth studies [5, 11].

In addition, 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 (± 50 mm) 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 2. Summary of the laboratory and field test results.

Test slab ID	Age at testing	Avg. tensile bond strength (MPa) [COV %]		
		pre-wetting duration		
		none	1 h	6 h
Laboratory test program				
MC-20-XX-CON35	2 months	1.59 [25.9]	1.82 [19.0]	2.24 [7.8]
MC-35-XX-CON35	2 months	1.85 [42.0]	1.94 [27.5]	1.95 [23.5]
MC-50-XX-CON35	2 months	1.94 [48.7]	1.81 [47.2]	1.84 [43.5]
MC-20-XX-EXM	2 months	2.15 [9.5]	2.37 [17.4]	2.31 [14.0]
MC-35-XX-EXM	2 months	2.92 [10.7]	2.90 [11.1]	2.43 [7.7]
MC-50-XX-EXM	2 months	2.18 [19.9]	3.11 [8.4]	2.77 [18.1]
Field test program				
MC-35-XX-CON35	2 months	1.87 [12.4]	1.79 [13.9]	1.63 [24.6]
MC-35-XX-CON35	1 year	1.77 [12.4]	1.74 [19.8]	1.69 [26.2]
MC-35-XX-CON50	2 months	1.80 [16.2]	1.52 [45.3]	1.62 [22.0]
MC-35-XX-CON50	1 year	1.93 [16.2]	1.71 [24.2]	1.84 [11.2]

5 Conclusion

The following conclusions and recommendations resulted from this project.

1. When normal and higher strength (about 35 MPa 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. Use of a repair or overlay material designed to be low-shrinkage (e.g., with the use of 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 aforementioned conclusions are based on very specific combinations of substrates, repair materials, and moisture conditioning times. Further studies on different combinations of repair materials and substrate concretes, with a range of ageing and moisture conditions, is necessary. 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. It is necessary to define more clearly in guidelines and codes 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. In view of determining when the superficial moisture condition of the substrate is suitable for concrete placement after pre-wetting, electrical impedance meters appear to provide a simple and valuable solution.

The experimental works reported in this paper have been financially supported by the U.S. Bureau of Reclamation and the Natural Sciences and Engineering Research Council (NSERC) of Canada. The authors wish to express their gratitude to Mr. Mathieu Thomassin and Mr. Bret Robertson for their technical contribution.

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