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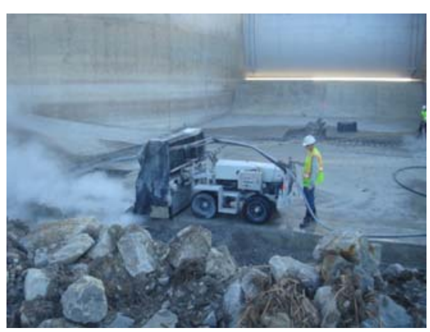
Report Number MERL 12-17

Best Practices for Preparing Concrete Surfaces Prior to Repairs and Overlays







U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

May 2012

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Best Practices for Preparing Concrete Surfaces Prior to Repairs and Overlays

by

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Best Practices for Preparing Concrete Surfaces Prior to Repairs and Overlays

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Introduction

Purpose and Need

One of the biggest problems impacting the long-term performance of concrete repairs and bonded overlays is cracking of the repair material and repair material debonding from the concrete substrate. There are many purposes for concrete repair, including prolonging the useful service life of a deteriorated or distressed structure or element, restoring the load carrying capacity and the stiffness, and strengthening the structure. In most cases, for the repair to be successful, monolithic action (acting as one unit) between the repair material and the substrate concrete (the composite repair system) is needed. A prerequisite for monolithic action is long lasting bond between the existing concrete substrate and the repair material.

The mechanisms and characteristics of bond between existing concrete and repair materials have been researched in the past. It is a very broad and generic engineering task. Thus, the scope of existing guidance and specifications on methods to ensure obtaining long-term bond is limited. This is mainly due to the lack of understanding of some of the factors that affect bond strength and durability of in situ repairs. Despite the relatively large pool of theoretical knowledge, the practical issues related to surface preparation of existing concrete to achieve long lasting bond are still inadequately addressed. This is demonstrated by the small number of ongoing research projects in the field, the current state of limited knowledge, the codes of practices, and in some cases the continued poor performance of repairs and overlays.

Of critical importance to long-term bond is the substrate surface preparation prior to application of repair materials. Regardless of the cost, complexity, and quality of repair material and application method employed, the quality of the surface preparation of the substrate prior to repair will often determine whether a repair project is a success or a failure, and whether a repaired structure meets the design objectives.[1] [1]

Objective and Scope

The objective of this study is to identify the key physical characteristics of a concrete substrate needed to ensure successful, long-term repairs and overlays, and to develop a "Suggested Guide Specification for Concrete Surface Preparation Prior to Repair" (Suggested Guide Specification).

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[1] Numbers in brackets refer to citations at the end of the report.

To meet this objective the following tasks were performed:

- A review of existing literature to establish fundamental factors and characteristics of the concrete substrate preparation prior to repair
- Summarize the results of the International Research Project, "Development of Specifications and Performance Criteria for Surface Preparation Based on Issues Related to Bond Strength" (located in appendix B and summarized in chapter 3)
- Based on the first two tasks, develop practical guidelines in the form of a "Suggested Guide Specification"

Applicability to Concrete Repair Practice

Repair and strengthening of existing concrete structures are among the biggest challenges civil engineers face today and will have to face in the years to come. The current focus on sustainable development, which emphasizes repair instead of new construction, bolsters this trend. In this same regard, repairs to concrete structures need to be as long lasting as possible.

Engineers, researchers, and contractors are devoting considerable effort towards improving the durability of concrete repairs. As described above, one of the critical aspects of durability of concrete repairs and overlays is a lasting and sufficient bond between a repair material and the existing concrete substrate. A critical component in achieving adequate bond is the concrete surface preparation and condition prior to application of a repair material.

This project was structured to benefit concrete repair design and practice immediately. This report and Suggested Guide Specification provide a state-of-the-art review of the factors critical to surface preparation of concrete substrates for repair and bonded overlay. They can be used to modify and improve current project specifications, field practices, and quality control.

This report is intended to provide accurate information on current knowledge and best practices, and to determine areas where further work may be needed in establishing reliable concrete surface preparation procedures and criteria. Recommendations for future research are also presented.

Outline of the Report

Chapter 1 presents some analysis related to bond and its development in concrete repair composite systems. This information was obtained from the literature review and the authors' previous work and experience.

Chapter 2 reviews the fundamental factors related to concrete substrate condition affecting bond strength. Relevant results from the literature review and knowledge from the authors' experience are also included.

Results and conclusions from the International Research Project are summarized in chapter 3. The influence of surface roughness parameters, tensile and shear bond and their relationship, effects of load eccentricity in pull-off bond strength test results, and effects of carbonated concrete surface on the bond development are summarized in this chapter.

Appendix A offers a Suggested Guide Specification, which can serve as a basis for repair specifications or as a source to provide additional specification guidance in existing repair specifications.

Further research needs, especially in the field of optimum moisture conditioning of the concrete substrate prior to repair, are also identified.

Limitations and Further Research

The scope of this project was large, and not all relevant aspects could be studied. The focus of this study was to identify relevant characteristics of some of the fundamental factors affecting the performance of concrete repairs and bonded overlays. These repairs and overlays are subjected to differential shrinkage and cracking, and possible debonding behavior, which impacts bond strength and durability.

The scope of the experimental study was limited to conventional Portland cement concrete substrate materials and cement-based repair materials with normal weight aggregates. The reported results, conclusions, and recommendations may not necessarily apply to special concrete substrates and/or special repair materials, such as polymer-based and polymer-modified materials, fiber-reinforced materials, lightweight aggregate materials, etc. Some of the provisions in the Suggested Guide Specification might not be applicable for such special materials.

The Suggested Guide Specification included in this project contains the relevant results of the International Research Project, "Development of Specifications and Performance Criteria for Surface Preparation Based on Issues Related to Bond Strength." However, it also includes substantial information based on a review of the best state-of-the-art knowledge and field practices in the concrete repair area.

This report should not be considered the final guide to surface preparation to obtain long-term performance of concrete repairs. As discussed here, further work is needed in a variety of areas. As further studies are conducted and solid conclusions are developed, the report should be updated to account for the latest developments and results.

In this respect, it is important to realize that the report also serves as a basis for further work. In particular, our research showed that further work is needed on the development of reliable methodology for evaluating optimum moisture conditioning of a given concrete substrate; only then can guidance on this important parameter of concrete surface preparation be drafted.

Chapter 1

Characteristics of Repair Material Bond

The characteristics of adhesion, or “bond,” can be perceived from two different perspectives: (1) the conditions and kinetics of joining two materials, taking into account different bond mechanisms; and (2) the quantitative measure of the magnitude of adhesion, usually expressed in terms of stress or energy required to separate the two materials. Available information on repair strength commonly refers to the stress required to separate the repair from the substrate [2].

The term “adhesion” describes the condition in the boundary layer between two connecting materials with a common interface. Adhesion mechanisms can be divided basically into mechanical interaction, thermodynamic mechanisms, and chemical bonding. Mechanical adhesion in repaired concrete members relies on the hardening of the repair mixture inside the open cavities and asperities 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 into small cavities of the substrate. The amount of material drawn into the surface is dependent on the substrate surface moisture condition and size of the cavities. The influences of substrate moisture condition on bond strength are discussed in section Chapter 2.

It is important to note that mechanical adhesion in tension differs significantly from that in shear. For example, a high interface roughness may improve shear bond strength, whereas tensile bond strength primarily depends on vertical anchorage in pores and voids (figure 1).

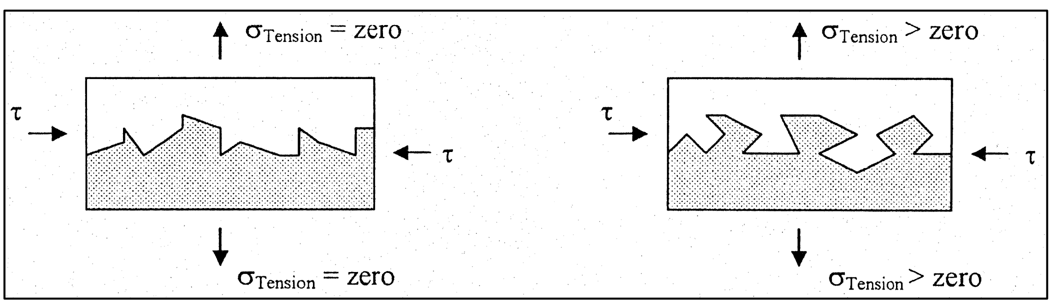

Figure 1. Schematics of mechanical shear and tensile bond between substrate and repair, resulting from interlock mechanisms [3].

All bond mechanisms act on the true surface area, as opposed to the geometric surface area, and the contact surface area, also termed “effective surface area” (figure 2).

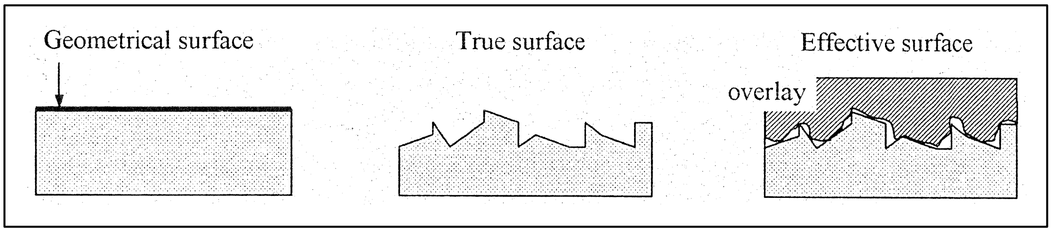

Figure 2. Geometrical, true, and effective surface areas between substrate and overlay [3].

Pigeon and Saucier [4] considered the interface between old and new concrete to be very similar to bond between aggregates and cement paste. According to them, a wall effect exists between the overlay and substrate, resulting in a transition zone that creates a layer of weakness (figure 3), although others disagree.

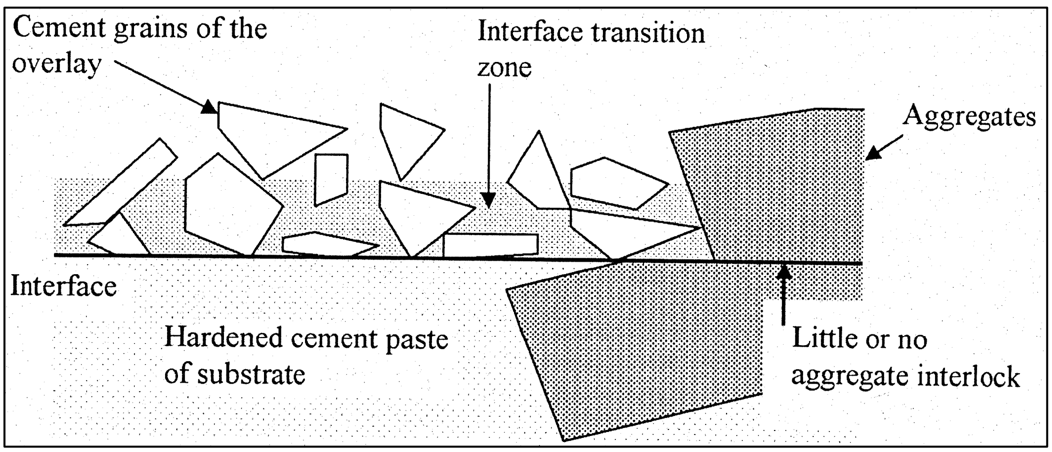

Figure 3. Transition zone between substrate and overlay, according to Pigeon and Saucier.

However, the statement that the transition zone "creates a layer of weakness," in the opinion of others, is only justified when the surface preparation for repair is inadequate. Otherwise, the transition zone may be a zone of strength rather than weakness.

Emmons and Vaysburd [5] presented an idealized model of a surface repair as a three-phase composite system consisting of existing concrete, repair material, and a transition zone between them (figure 4).

The authors state that the characteristics of the transition zone are a function of the properties of the substrate (adherent), the properties of the repair material (adhesive), and the substrate surface preparation. Environmental factors, such as temperature and moisture, play an important role on the properties of the interface region and, consequently, on interfacial bond development.

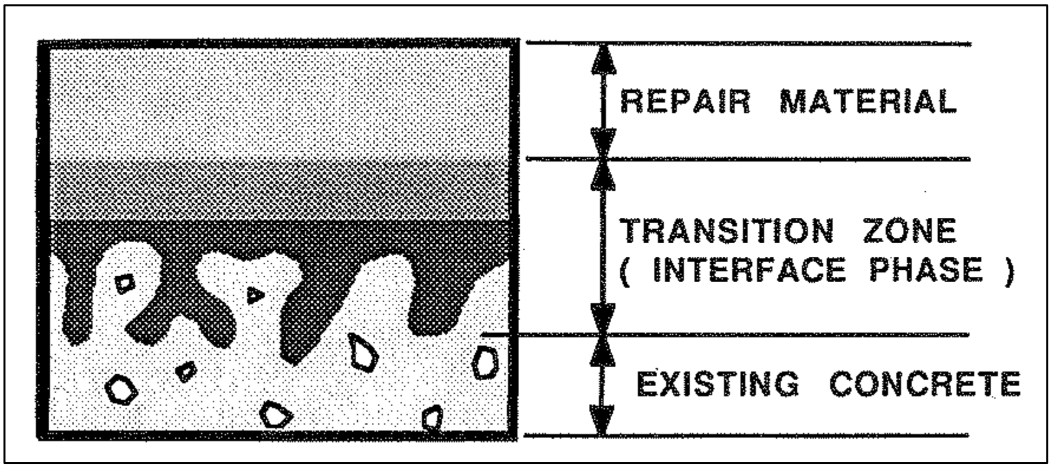

Figure 4. Idealized model of a surface repair system [5].

A possible macroscopic characterization of the quality or degree of adhesion is obtained by the introduction of a transition zone along the geometrical interface between the adhesive and adherent. The thickness of the transition zone is the sum of the lengths in the adherent and the adhesive zones, where interactive forces of any nature change the mechanical nature of the original continuum [6].

Adherence between a repair and the existing concrete in a mature composite repair is a case of adherence between two solids. One of the solids (the repair material) formed as a result of setting and hardening of a semi-liquid substance, which was placed on the prepared surface of a second substance in a solid state (existing concrete).

The following major factors that influence the formation of the transition zone and degree and durability of bond are:

- Properties of substrate concrete and the prepared surface
- Properties of repair material
- Absorption of the substrate
- Adhesion and adequacy of adherence of the repair material in both uncured and cured states
- Environmental conditions

The repair material and concrete substrate, when viewed as a classical glued connection, can be considered as a “contact couple” where the repair acts as the glue. In this case, the bond strength can be seen as the result of mechanical bond, pure adhesion, cohesion, and contraction of the repair material. The first three factors increase the bond strength, and contraction decreases it.

Adhesion and cohesion are two interconnected parts of the process of forming of the contact zone. However, the most important component of bond strength for concrete repair is the adhesion.

The mechanical anchorage of the repair is related to the roughness and the porosity of the substrate. When estimating the effect of a substrate on bond, not only its roughness, but also the size and form of the protrusions must be taken into account. In the case of extended, but gentle, unevenness, an increase of the bond strength only comes with the increase of the actual contact area. The specified properties of the repair material (e.g. consistency, method of compaction, etc.) have a considerable influence on the mechanical anchorage, the adhesion, and the bond strength. The amount of the bond strength between the concrete and the repair material also depends to a great extent on the cohesion of the repair material, and that is governed by the strength of the binder (cement, fly ash, etc.), its mineralogical components, and by curing condition.

Chapter 2

Factors Influencing Bond Strength

Condition and Texture of the Substrate

General

Surface preparation and cleaning of the concrete substrate is generally considered the most crucial step in a concrete repair project. A poorly prepared surface will always be the weak link in a repair, no matter how good the repair material might be. Surface preparation includes the removal of damaged and/or deteriorated parts of the substrate concrete and previously applied coatings, whereas cleaning commonly refers to the removal of loose particles and contaminants on the surface. Surface cleanliness is also very important in concrete repairs, as any loose debris, dirt, grease, or other surface contaminants can act as bond breakers. Obtaining a sound and clean substrate requires quality workmanship. Findings and recommendations made from research on bond durability are meaningless unless proper site practices can be ensured.

Methods of Roughening the Substrate Surface

Common surface preparation methods include mechanical roughening and blast methods using abrasives, high pressure water, or a mixture. The use of heavy mechanical techniques such as jackhammers, drills, and scabblers usually results in the formation of microcracks in the substrate surface, which have a detrimental effect on bond strength [7, 8]. However, sandblasting after the use of heavy mechanical methods can remove the damaged concrete and provide a sound interface [9]. The authors of this report believe that water jetting of sufficient pressure would provide the same benefit as sandblasting. Warner et al. [7] achieved good bond strength on surfaces that were sandblasted without prior roughening.

According to Silfwerbrand [10], water jetting results in a sound, rough, and clean concrete surface, removing deteriorated concrete and leaving sound concrete. Kauw and Dornbusch [11] discussed the effects of applied pressure during water jetting on the quality of the concrete surface. They concluded that water jetting is a good method of concrete removal but has to be specified carefully with consideration of the properties of the concrete to be treated.

Interface Texture

Interface texture can be divided into macroscopic, microscopic, and submicroscopic texture (figure 5).

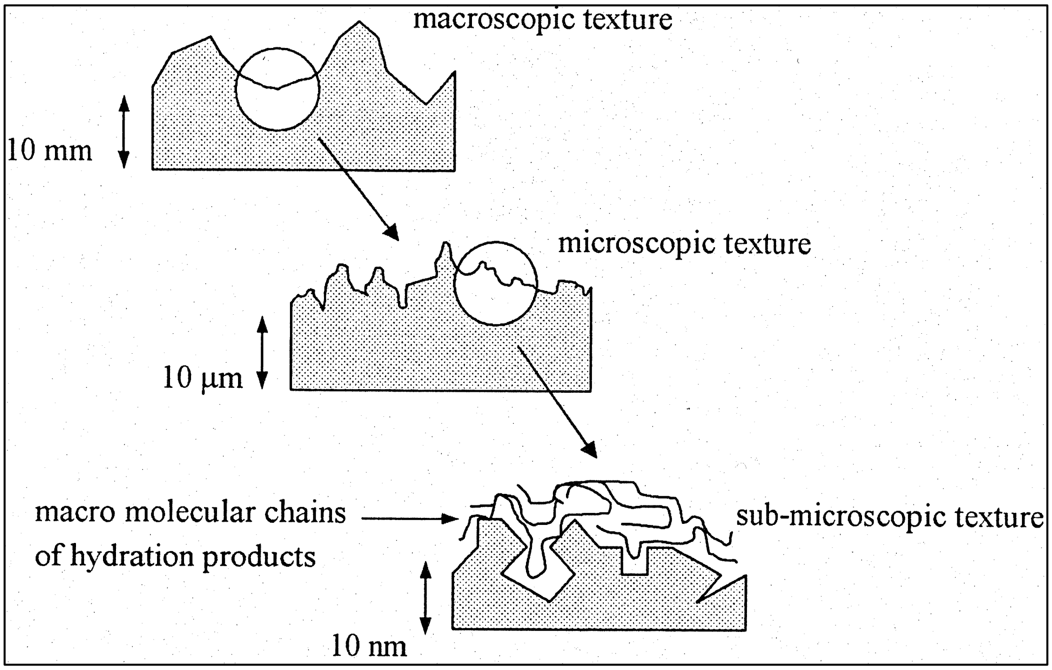

Figure 5. Macroscopic, microscopic, and submicroscopic surface texture [3].

Interface texture is commonly expressed in terms of roughness. Interface roughness depends, to a large extent, on the method of substrate surface preparation. Mechanical methods of concrete removal normally leave the substrate surface much rougher than blast methods. The magnitude of surface roughness for concrete repairs is commonly measured in millimeters (mm). The different test methods for evaluating surface roughness are described in chapter 3.

A number of researchers have linked interface roughness to bond strength. Silfwerbrand [12] compared interface strengths resulting from different surface treatments and different roughnesses. He concluded that the threshold value for tensile bond strength improvement lies in the range of the surface roughness of sandblasted surfaces. An increase in surface roughness beyond this value did not seem to increase tensile bond strength.

Also, as discussed by Beushausen [3], the tensile pull-off test method is not very susceptible to the effects of surface roughness. He states that generally, it appears reasonable to assume that interface roughness has an influence on shear bond strength, while it is of minor importance for tensile bond mechanisms.

The actual influence of interface roughness on bond strength also depends on a range of other parameters such as material strength and effective surface area. Interpretation of bond properties in terms of individual parameters therefore appears problematic and should be done with caution.

Moisture Condition

The substrate moisture condition can have a significant influence on bond strength. A dry, "thirsty" concrete surface tends to pull water from the overlay material. If it pulls too much water into the substrate, the repair material may not hydrate properly, which may result in a weak interfacial repair layer and low bond strength. A surface that is too wet tends to dilute the repair material at the interface by increasing the water/cementitious materials ratio, which leads to lower material strength, increased shrinkage, and low bond strength. Water in open pores may further prevent the interlocking effect by preventing cement particles from entering the pores. Free water at the surface substrate can destroy the bond completely.

Zhu [13] has found experimental signs of optimal moisture, but the moisture influence on the bond was so small that it was difficult to discern between moisture influence and scatter of test results.

In general, the opinions on the effects of substrate moisture differ significantly between individual researchers and engineers [4]. Li et al. [14] measured the bond strength of repaired specimens after freeze-thaw cycles and found that different repair materials correspond to different optimum interface moisture conditions at the time of casting.

Repair Material Properties

The fresh repair material properties are important, both for early age bond strength development and bond durability. Workability, compaction, and consolidation of the freshly placed repair influence its ability to fill open cavities and voids on the substrate concrete surface, which directly impacts the effective contact area between the repair material and substrate. A relatively fluid mixture (made so without excess water) further enhances capillary suction in the substrate and, therefore, improves physical anchorage in substrate surface pores and cavities. Horizontal repairs, on pavements or bridge decks for example, and large application areas on vertical and overhead surfaces, may be carried out with concrete of high fluidity. Self-leveling mortar applied for overhead repair using formwork was found to have very good bond properties in terms of its ability to fill cavities at the interface. The fact that good anchorage can be achieved without the effects of gravity implies that capillary suction of the old concrete plays an important role in bonding mechanisms.

However, small surface repairs are commonly made with premixed, relatively stiff mortars, which are applied with a trowel. This leads to a smaller contact area between the substrate and overlay and lower capillary suction of the substrate, compared to overlays of higher fluidity, potentially resulting in lower mechanical and chemical bond strength. For these kinds of mortars, bonding agents might be helpful to improve adhesion.

As shown above, overlay workability plays an important role for bond strength. However, even with relatively stiff overlays, good bond can be achieved if the overlay is applied with sufficient pressure and workmanship is good.

The hardened repair material property that directly influences bond strength is its mechanical strength. However, of equal importance are the material properties that influence the development of stresses in the repair and at the interface, such as shrinkage, elastic modulus, thermal coefficient, creep, permeability, and additions like fiber reinforcement and admixtures, etc. Unfortunately, the combined influence of different material properties on bond strength is generally difficult to assess. Therefore, research has commonly been carried out on the influences of individual material properties on bond strength and bond durability.

The significance of repair material mechanical strength is immediately apparent when the characteristics of the interface transition zone are considered. The location of "bond failure" (i.e., in the substrate, at the interface, or in the repair material) indicates the zone of weakness in the system (and may not be actual "bond failure"). For the case of "bond failure" in the repair material, it is important to understand the prevailing mode of failure.

Concrete Carbonation

According to Schrader [15], carbonation of the substrate can result in a soft surface and dusting, which may result in poor bond strength if an overlay is applied. Similar test results were obtained by Gulyas et al. [16], who found that substrate carbonation can decrease bond significantly. By contrast, Block and Porth [17] found that substrate carbonation does not affect pull-off bond strength. These contradicting results show the problems inherent in interpreting bond test results for complex systems in terms of a single test parameter. The actual differences in results can be explained by likely differences in surface preparation, repair material application, and curing.

Substrate Temperature

The substrate temperature at the time of repair placement was found to have a significant effect on shear bond strength development [18]. Cold substrates (40 degrees Fahrenheit (°F), 4 degrees Celsius [°C]) resulted in lower initial bond strength but higher long-term bond strength, compared to substrates of higher temperature (70 or 100 °F, 21 or 38 °C). This effect probably relates to the effects of hydration of the cement paste. Low temperatures generally slow down the hydration rate. At slow hydration rates, the hydration products have sufficient time to diffuse uniformly throughout the cement paste, which consequently increases later age strength.

Chapter 3

Summary of the International Research Project[2] and Results and Conclusions

Specific Objectives and Experimental Program

The research activities in this international project (appendix B) were conducted in four countries by the following organizations:

- Laval University, Quebec (QC), Canada
- Bureau of Reclamation (Reclamation), Denver, Colorado, USA
- University of Liége, Liége, Belgium
- Warsaw University of Technology, Warsaw, Poland
- Vaycon Consulting, Baltimore, Maryland, USA

This research project was developed as a result of prior research activities of some of the research partners. Various factors were studied to try and determine test methods that would predict field performance of cementitious repair materials [19, 20]. However, as a consequence of these studies, the authors determined that further research into the fundamental characteristics of repair material bonding and durability were needed.

The primary objective of this research project was to perform studies that would provide data for the development of performance criteria for surface preparation of existing concrete prior to repair and overlay.

The specific objectives of the project were to:

- Evaluate existing methods for assessment of roughness of a prepared surface and to select the most appropriate method for field use

- Establish a correlation between shear bond strength, pull-off tensile strength, and surface roughness

- Evaluate the effect of load eccentricity in a tensile pull-off test on bond strength test results

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[2] "Development of Specifications and Performance Criteria for Surface Preparation Based on Bond Issues Related to Bond Strength"

- Determine the optimum substrate moisture condition for cementitious repairs and to determine a field test to evaluate the moisture condition of the particular concrete substrate

- Evaluate the effect of a carbonated concrete substrate on bond strength

- Develop performance criteria and "Guide Specifications for Concrete Surface Preparation Prior to Repair" for surface preparation

The following factors related to the concrete substrate to be repaired/overlaid were taken into consideration:

- Concrete substrates are different from each other in quality, service exposure, and age.

- Concrete substrates are physically and chemically very complex.

- The complexity has to be considered on the basis of scale, which depends on a particular situation.

- Practical answers and guidance on achieving an optimum bond in the composite repair/overlay system presently depend more upon broad judgment than detailed knowledge.

The following concrete surface treatment methods were investigated in the program:

- Chipping hammer
- Sandblasting
- Shotblasting
- Waterblasting

The experimental program was divided into six tasks described in the following sections.

Suitable Concrete Surface Roughness Parameters

General

Common surface preparation methods include mechanical roughening and blast methods utilizing abrasives or water, or mixtures of them.

Interface concrete texture is commonly expressed in terms of roughness, which depends, to a large extent, on the method of substrate surface preparation.

The substrate roughness is often considered an important factor affecting bond strength between the existing substrate and repair material. However, this subject has been controversial over the years. Some researchers reported that bond test results have shown that surface roughness has only a minor influence on tensile bond.

Silfwerbrand [12] concluded that there could be a roughness “threshold value” beyond which further improvement in roughness would not enhance the bond strength. At the same time, it also remains the opinion of others in the field that a rougher surface is beneficial to bond strength. Tschegg et al. [21] compared roughness of 0.07 inch (1.75 millimeters [mm]) to 0.03 inch (0.65 mm) on waterblasted surfaces and found better bond characteristics for the rougher interface.

Beushausen [3] states that it appears reasonable to assume that interface roughness has an influence on shear bond strength, while it is of minor importance for tensile bond mechanisms.

Test Program

A variety of approaches and test methods have been used over the years to characterize the surface roughness of concrete. The objective of this task was to identify the most suitable technique for field and laboratory use, as well as the most relevant quantitative roughness characteristics. The research studies in this task were performed at the University of Liége and Reclamation.

The following techniques were analyzed on a comparative basis:

- Comparative sample profile chips - Concrete surface profile (CSP) chips, described in International Concrete Repair Institute (ICRI) Guideline No. ICRI 310.2-1997, “Guide for Selecting and Specifying Concrete Surface Preparation for Sealers, Coatings, and Polymer Overlays [22]; utilize nine plastic profile chips. As a set, these plastic profiles replicate degrees of roughness up to a roughness of about ¼ inch (6 mm). These benchmark profiles may be referenced in specifications, material data sheets, and repair application guidelines to effectively communicate surface preparation requirements.

  Sand spread test – American Society for Testing of Materials (ASTM) E965, “Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique” [23]. A volume of sand is spread on a surface, and a measurement of the total area covered is determined. The technique is designed to provide an average depth value of only the pavement macrotexture and is considered insensitive to pavement microtexture characteristics. The roughness Rt then is calculated from the diameter of the circle d, using the following equation:

$$Rt = \frac{40\,V}{\pi d^2}$$

where V is the volume of the sand.

- Mechanical profilometry - A high-precision extensometer is moved over the surface to obtain a 3-dimensional mapping (x, y, z coordinates) from which roughness parameters are computed.

- Laser technique - The superficial elevation (distance from the laser beam source) of each point is calculated on the basis of the laser beam transit time.

- Opto-morphometry technique - An analysis is made of shadows produced by the superficial roughness of the surface (Moiré fringe pattern principle).

- Microscopic methods.

Experiments at the University of Liège

Theoretical analyses of all techniques listed above were conducted. The experimental program included surface treatments of prefabricated concrete slabs 12 by 12 by 2 inches (300 by 300 by 50 mm). The following concrete surface treatments were used:

- Grinding
- Sandblasting
- Shotblasting
- Milling

The surface roughness of each treatment was evaluated with the following techniques:

- Mechanical profilometry
- ICRI CSP chips
- Sand spread method
- Microscopic method

Based on results of the experiments, the most practical techniques for evaluation of concrete surface roughness under field conditions is the ICRI CSP chips.

Experiments at Reclamation

Twelve concrete slabs, 22 by 46 by 6 inches (560 by 1,170 by 150 mm), were manufactured from 6,000-pound-per-square-inch (psi) (42-megapascal [MPa]), ready-mixed concrete. The slabs were moistened for 72 hours, and then they were aged and monitored for drying shrinkage under controlled conditions for about 4 months until volumetric stability was reached.

The top surface of each slab was then prepared using a chipping hammer, sandblasting, or waterblasting. Four slabs were prepared by each of the surface preparation methods.

After completion of surface preparations, a series of surface characterization tests was performed, including concrete substrate integrity and surface roughness evaluation. The integrity of the prepared surfaces was evaluated using the Schmidt hammer test [24]. Forty readings were taken on each slab.

Results from the Schmidt hammer tests showed that the sandblasted method of surface preparation resulted in concrete surfaces with the highest average surface strength, while surfaces prepared by the chipping hammer had significantly lower average surface strengths.

The surface texture characteristics were evaluated using the ICRI CSP chips method (ICRI 310.2-1997), opto-morphometry method, and ASTM E965.

The results of these experiments indicated that the "visual" ICRI method correlates well with the other quantitative methods. In addition, results of the Schmidt hammer tests indicate that chipping the surface weakens it relative to sandblasted surfaces.

Conclusions

Among the techniques available today, the method which appears to be best suited for field assessment of surface texture is the CSP chip technique developed by ICRI. Use of the chips is rapid, easy, and yields reliable information, irrespective of the surface orientation. However, this method has the following limitations:

- It is subjective, because it is based on visual comparison of the chips with the in situ surface roughness

- Since it was intended by ICRI specifically for concrete surface preparation for polymer overlays, sealers, and coatings, the profile range of up to ¼ inch (6 mm) is not enough for use with rougher surface profiles that can frequently occur in the concrete repair field.

We recommend it for practical use (specifications and quality control). If the roughness range of the chips was increased to a value on the order of ¾ inch to cover more cases, it would be more useful. In doing so, it might be desirable to develop two different sets: one set for impact methods (i.e., breakers) and one set for abrasion methods. As stated by ICRI, for a given roughness level, the CSP visual evaluation can be significantly influenced by the actual surface texture.

The opto-morphometry yields reliable quantitative data, but the equipment available today is not easily used in daily field applications. Nevertheless, with the rapid technological development in this area, the availability of suitable optical devices can be foreseen in the near future. This would allow even more rapid and objective assessment.

The sand patch method can provide a good indication of the surface profile, but its use is limited to horizontal surfaces with low-range roughness.

Relationship Between Tensile Bond, Shear Bond, and Substrate Roughness

General

The main objective of this task was to establish the relationship between both tensile and shear bond strengths and the substrate roughness. Two experimental programs were implemented at Reclamation and at Laval University [25] to meet the objectives of this task.

Differential volume changes between substrates and repair materials induce internal stresses, in particular shear stresses, and in the case of overlays, may cause both shear and tensile stresses at the interface [3]. These differential changes are most prevalent just after application of the repair material. Most cementitious repair mortars can experience shrinkage during strengthening and drying.

For concrete repairs and overlays, bond strength is generally defined as the “tensile strength perpendicular to the interface plane.” However, mechanical adhesions in tension and in shear differ significantly. For example, a high interface roughness may improve shear bond strength, whereas tensile mechanical bond strength primarily depends on vertical anchorage in pores and voids. Typically, standards and specifications for concrete repair define bond strength in terms of tensile strength alone, which is problematic when shear strength is the preferred parameter.

When specifying and/or evaluating bond strength values, it is important to consider the dominant interface stress condition experienced by the actual structure. Talbot et al. [26] investigated the influence of different interface textures and concluded that smooth surfaces, as well as sandblasted surfaces, experienced a significant loss of bond strength with time. On the contrary, surfaces that were roughened mechanically and then subsequently sandblasted exhibited good bond durability. This may be because high interface roughness, as it is commonly achieved in practice for field repairs, improves the resistance against interface shear stress resulting from a repair material's shrinkage.

Several studies agree that shear bond strength is higher than tensile bond strength. However, there is no agreement on the magnitude of the difference. The reported mean ratio (shear bond strength divided by tensile bond strength) ranges from 1.20 to 2.40 inches (30 to 60 mm) according to different studies that were reviewed. That range is obviously too wide for converting satisfactorily the pull-off test results to shear bond strength.

Test Program

Experiments at Reclamation

The experiments were carried out on twelve 22- by 46- by 6-inch (560- by 1,170- by 150-mm) test slabs prepared as described above using waterblasting, sandblasting, and chipping hammer techniques, and then overlaid with concrete.

For each surface roughness, 36 pull-off tests [27] and 36 shear bond (torsional) [28] strength tests were performed – 3 shear and 3 tensile bond strength for each slab. Pull-off and shear tests were performed using a manually driven hydraulic device (manufactured by Germann Instruments).

The test yielded the following results for the different surface preparation conditions under investigation:

- The average pull-off bond strength for waterblasted surfaces was 276 psi (1.9 MPa); the average shear bond strength was 232 psi (1.6 MPa). Hence, tensile pull-off strength was 1.19 times higher than shear strength for waterblasted surfaces.

- The average pull-off strength for sandblasted surfaces was 232 psi (1.6 MPa); the average shear bond strength was also 232 psi (1.6 MPa). Thus, there was no difference between pull-off and shear bond strength for sandblasted surfaces.

- The average pull-off strength for surfaces prepared using chipping hammer was 189 psi (1.3 MPa); the average shear bond strength was 290 psi (2.0 MPa). In this case, shear bond strength was 1.53 times higher than tensile pull-off strength.

Experiments at Laval University

Two series of 25- by 50- by 6-inch (625- by 1,250- by 150-mm) concrete test slabs were manufactured for the test program. In each series, 16 slabs were cast. The first series was prepared with a 3,500-psi (25-MPa) concrete mixture, while the second series was prepared with a 5,000-psi (35-MPa) concrete mixture.

The following techniques were employed for surface preparation of the experimental slabs' top surfaces prior to overlay application:

- Sandblasting
- Shotblasting
- Waterblasting
- Scarifying
- Chipping hammer

After completion of the surface preparation operations, characterization of surface roughness was performed. The slabs were then overlaid with a 6,500-psi (45-MPa) concrete mixture.

All repaired slabs were characterized for pull-off tensile bond strength, as well as shear (torsional) bond tests.

Surface roughness was evaluated using two methods: optical profilometry and ICRI CSP chips (ICRI 310.2-1997). The largest half-amplitude values (0.06 – 1.8 inch; 1.50 – 3.75 mm) were recorded for waterblasted and hammer-chipped surfaces. The lowest half-amplitude values were recorded respectively for scarified, shotblasted, and sandblasted surfaces (< 0.4 inch; 1.0 mm).

All 32 repaired concrete test slabs were evaluated for bond strength. On each slab, 16 pull-off and four shear bond strength tests were performed. The test yielded the following results for the different surface preparation conditions:

- **Sandblasted surfaces**
  Half-amplitude roughness: 0.03 inch (0.65 mm)
  Pull-off bond strength: 323 psi (2.23 MPa)
  Shear bond strength: 218 psi (1.50 MPa)

- **Shotblasted surfaces**
  Half-amplitude roughness: 0.03 inch (0.70) mm
  Pull-off bond strength: 312 psi MPa (2.15)
  Shear bond strength: 225 psi MPa (1.55)

- **Scarified surfaces**
  Half-amplitude roughness: 0.01 inch (0.25 mm)
  Pull-off bond strength: 297 psi (2.05 MPa)
  Shear bond strength: 236 psi (1.63 MPa)

- **Waterblasted surfaces**
  Half-amplitude roughness: 0.06 – 0.99 inch (1.5 – 2.1 mm)
  Pull-off bond strength: 319 psi (2.2 MPa)
  Shear bond strength: 276 psi (1.9 MPa)

- **Hammer-chipped surfaces**
  Half-amplitude roughness: 0.09-0.12 inch (2.25 – 3.00 mm)
  Pull-off bond strength: 196 psi (1.35 MPa)
  Shear bond strength: 145 psi (1.00 MPa)

Conclusions

When considering the relationship between interfacial pull-off bond and shear bond strengths in composite repair overlay systems, the test results here do not exhibit the same trends as often reported or described in the literature (in fact, reported hard data comparisons are extremely scarce).

No general correlation could be established because the various surface preparation techniques result in different types of profiles and induced defects. The combination of these parameters influences pull-off bond and shear bond strength measurements in different ways.

Relating interface shear and tension test results in a highly heterogeneous medium such as a concrete composite is, in fact, questionable as both rely on different combinations of bond mechanisms, which are affected to varying degrees by the interface and substrate characteristics (adhesion, friction, interface roughness and geometry, mechanical integrity of the substrate, etc.).

The pull-off tensile bond test is the only one commonly used in practice because the equipment is widely available, and it is relatively easy to carry out in the field. Shear (torsional) tests may also be performed onsite, but they are very seldom used for a number of reasons; the most significant reason is probably the absence of specification guidance.

The tensile pull-off test itself has a number of potential shortcomings, which must be considered in the analysis of results. The first problem addressed earlier is possible misalignment of the testing apparatus, which leads to uneven stress distributions and can potentially exert a significant influence on measured strength values. Another problem that is commonly encountered with tensile pull-off tests is that failure often occurs outside the interfacial zone, either in the repair material or within the existing substrate. When such a failure occurs, the recorded maximum stress merely represents a lower bound value for interface bond strength. A third problem encountered with the pull-off test is that the coring operation (part of the test procedure) may damage the interface between the repair and the substrate, which is likely to reduce the recorded pull-off strength.

Effect of Load Eccentricity in a Tensile Pull-off Test

General

For the identification of tensile bond strength, a force must be applied perpendicular to the repair/overlay interface plane. Any misalignment of the pull-off force leads to stress peaks, which might have a significant influence on measured bond strength values. Misalignments might be induced by the core drilling process, an uneven substrate surface, or the test devices and are generally difficult to avoid under in situ testing conditions. A combination of misalignments from different sources might intensify the problem so that the measured stress at failure does not represent actual bond strength.

Vaysburd and McDonald [29] observed that controlling the eccentricity of the applied load in a bond pull-off test is one of the critical factors affecting the test results. Load eccentricity depends on the normality of the drilling relative to the substrate and on the accuracy of positioning the metal disk on top of the core. Load eccentricity can lead to a very substantial increase in maximum stress at the core periphery. Another problem in avoiding eccentricity is the difficulty in keeping the core's substrate-repair interface perpendicular to the tensile force.

The pull-off tensile test is also used prior to application of the repair to evaluate the integrity of the prepared concrete substrate. Austin et al. [30] investigated the effect of misalignment on measured pull-off bond strength. The average eccentricity in the experiments performed was 0.06 inch (1.5 mm) at a depth of 2.0 inches (50 mm), which translates to an angle of inclination of 1.7°. The study concluded that such a misalignment caused an increase in maximum stress of the order of 20 percent (%) at the core periphery.

Cleland and Long [31] performed numerous tests on cores drilled to a depth up to 1.6 inch (40 mm) into the repair substrate and inclination to vertical of up to 20° in order to evaluate the effect that had on the measured pull-off bond strength. Those authors proposed a correction factor to apply to the measured results. The correction factor was based on the magnitude of the inclination angle.

Test Program

The main objective of the research performed in the International Research Project, with regard to the load eccentricity issues, was the evaluation of coring and/or load misalignment on the results from pull-off tests.

A theoretical analysis of the effects of misalignment on pull-off test results and the experimental program was initially performed at the University of Liége. A parallel experimental program was conducted at Reclamation.

The following variables were selected for investigation in the theoretical analysis and test programs:

- Theoretical and experimental pull-off study on monolithical substrates
  - Coring axis inclination: 0°, 2°, and 4°
  - Pulling force inclination in the quality/integrity test: 0°, 2°, and 4°
  - Core depth in the substrate: 0.6 inch (15 mm) and 1.2 inch (30 mm)

- Experimental pull-off study on repaired (composite) substrates
  - Coring axis inclination: 0°, 2°, and 4°
  - Core depth in the composite repair system: 4 inches (100 mm)
  - Core depth into the substrate: 1 inch (25 mm)

Theoretical Analysis

The analysis was performed to determine whether the two causes of misalignment (namely, core inclination of 4° and pull-off load inclination of 4°) affect the test results in a similar fashion. In both cases, the core depth analyzed was 1.25 inch (30 mm).

Both sources of misalignment yielded similar effects on the pull-off strength.

The numerical analysis results indicate that there is a stress concentration immediately below the core groove and that the maximum stress values are amplified due to the misalignment effect.

Experiments at the University of Liége

A series of six concrete slabs, 24 by 16 by 4 inches (600 by 400 by 100 mm), was manufactured for each of the three concrete strength mixtures:

4,350 psi (30 MPa), 5,800 psi (40 MPa), and 7,250 psi (50 MPa)

After 28 days of moist curing, the concrete slab top surfaces were prepared by sandblasting. Then, the pull-off tensile strength of the prepared concrete substrate was tested. The tensile pull-off tests were conducted using core depths of 0.6 and 1.2 inch (15 and 30 mm) and coring axis inclinations of 0°, 2°, and 4°.

Overall, the test results reveal that the pull-off strength reduction caused by misalignment, within the range of inclination angles investigated, is insignificant for all practical purposes.

While a net decrease in average pull-off strength values was observed for the 1.2-inch (30-mm) core depth, in comparison with the 0.6-inch (15-mm) core depth results, there was almost no influence of the concrete strength on the test results.

Experiments at Reclamation

A series of twelve 22- by 460- by 6-inch (560- by 1,170- by 150-mm) concrete slabs were manufactured using a 6,000-psi (42-MPa) concrete mixture.

After about 4 months, the top surface of each slab was prepared using the following surface preparation techniques: chipping hammer, waterblasting, and sandblasting.

Four slabs were prepared using each of the surface preparation techniques. Prior to application of a 3-inch (75-mm) overlay, the top surface of each slab was lightly sandblasted to remove any carbonated concrete.

The concrete mixture used for overlays had similar characteristics to the ones used for manufacturing the substrate slabs. The overlays were moist cured for 72 hours and aged for a minimum of 28 days prior to conducting the pull-off bond tests.

The cores were drilled through the overlays and 1.0 inch (25 mm) into the substrates. Pull-off tensile strength test series were carried out after coring with the inclination angles to verticality of 0°, 2°, and 4°. Thirty-six, 18, and 18 pull-off tests were conducted for each surface treatment, respectively.

Overall, the test results indicated that the average recorded bond strengths decreased at an increasing rate with the larger angle of inclination.

Conclusions

The general trends observed in numerical analysis and experimental programs for both the substrate integrity pull-off tests and bond in composite repair systems pull-off test reveal that the pull-off strength values decrease as the angle of misalignment increases. The deeper the coring is into the substrate, the greater is the effect of misalignment.

Actual experimental data, however, in the range of misalignment and other characteristics and factors studied, show less sensitivity of the pull-off test results than what was predicted through numerical analysis. In the “realcrete” experiments, substrate surface imperfections, air voids, microcracks, cracks, nonuniformity of roughness, etc., exert considerably more influence on the recorded pull-off values than misalignment, at least within the investigated relatively low misalignment range of up to 4°.

Thus, provided that core drilling is achieved quite accurately, and the rest of the pull-off test operations are achieved in overall good conditions, it can be concluded that small deviations from the vertical do not significantly alter the pull-off strength evaluation.

Evaluation of Moisture Conditioning in a Concrete Substrate

General

The influence of surface moisture on the bond between existing concrete and repair is an issue of significant importance. The moisture condition of the concrete substrate surface at the time of application of the repair material has a major influence on the moisture transport mechanism between the freshly applied repair material and existing concrete substrate.

Saturated Surface Dry conditioning of the substrate prior to application of cementitious repair materials is usually recommended and used, which underlies the "layman's" tendency to avoid problems, rather than achieving the most effective bond.

Various investigators came to the conclusion that different substrates and repair materials may require different interface moisture conditions at the time of casting to achieve optimum interfacial bond. The problem is that presently, there is no test method to determine the optimum moisture condition for a given combination of substrate and repair material.

Water is one of the critical factors influencing bond development between concrete and repair materials: it may accumulate at the interface or migrate through it in either direction as a result of mechanical (i.e., gravity), chemical (i.e., hydration) or physical (i.e., temperature gradients) driving forces.

Different moisture transport parameters affect the formation and behavior of the repair interfacial zone, such as diffusion and permeability coefficients, as the interface characteristics are indeed influenced by different forms of water interaction:

- First, moist conditioning of the substrate before the application of the repair system is a key consideration. Partial or total saturation of a concrete substrate is a common situation in repair works. Water along the interface may prevent adhesion to the repair system, with regard to polymer concrete, polymer modified Portland cement concrete, or Portland cement concrete [32].

- Second, water or aqueous solution movements may appear [33] due to migration and infiltration along the interface [34] or diffusion and capillary absorption from the zones to be repaired [32]. Resistance to these water movements will directly depend on the quality of the materials (i.e., the water to cement ratio, porosity, etc.).

In most situations, the saturation level at the interface appears to be a predominant factor in promoting the adhesion of the repair system.

Test Program

In a test program conducted at the University of Liège, two concrete surface moisture test procedures were investigated: an Initial Surface Absorption Test (ISAT) developed on the basis of a Queen's University of Belfast testing device [35], and a Modified Capillary Suction Test (MCST) developed at the University of Liège [36]. The objective was to correlate the moisture condition of the concrete surface to the water penetration characteristics evaluated through these tests.

A series of test specimens was made with three ordinary Portland cement concrete mixtures (4,400-, 5,800-, and 7,300- psi; 30-, 40- and 50-MPa compressive strength). Three different surface treatments were used (no treatment, sandblasting and waterjetting) before the specimens were stored in eight different moisture conditions to cover the range from 30 to 100 % relative humidity (RH).

Both the ISAT (permeability index) and MCST test methods yielded interesting results, and overall relatively good correlations with the concrete moisture content were observed, especially below 80 % RH.

ISAT results were shown to be insensitive to concrete compressive strength, at least in the range of those tested. Results are influenced by the substrate surface quality, but it is difficult to conclude whether this is due to surface roughness, microcracking, or a combination of both. The relatively high variation and dispersion characterizing the ISAT test results may stem from the difficulty of performing the test on rough concrete surfaces (for instance, after hydrojetting).

The MCST test yielded clearer trends and less dispersed information than the ISAT test, as well as a better correlation with water content measurement (wet and dry weighing measurements).

Satisfactory correlation was also found between the water absorption index and the capillary absorption coefficients determined using both tests.

Nevertheless, the investigated test procedures exhibited a few shortcomings, which prevent their use as practical tools. First, both tests are essentially dedicated to laboratory work, and their regular use in field conditions cannot really be considered. Second, the lower correlations found at levels of humidity exceeding 75 % significantly reduce the actual assessment reliability for moisture condition ranges that are typically present in a concrete substrate prior to repair. Not only does this affect the measurement itself, but obviously impacts the identification of the optimum moisture conditions as well.

Conclusions

Due to the complexity of the issue and the multiplicity of influencing factors affecting the evaluation of optimum moisture condition, the objectives of this task have only been partially met.

The findings demonstrate the effect of water in the substrate concrete superficial zone and the difficulty encountered in reliably evaluating the actual saturation level. For the repair systems considered in this task, it appears that optimum saturation levels for repair bond strength would lie somewhere between 55 to 90%.

Clearly, however, additional work is required to identify a methodology that could be used in field applications and, furthermore, to assess more precisely and reliably what the optimum moisture ranges are for cement-based repair materials.

Effect of Carbonated Substrate on Bond Strength

General

The effectiveness of mechanical adhesion of the repair material to the prepared concrete substrate is explained by the fact that the cement paste will penetrate through the roughness and open pore system of the substrate and, after hardening, induce cohesion interlocking and anchoring effects.

Carbonation occurs when constituents in the concrete react with carbon dioxide and moisture to produce calcium carbonate. It typically advances inward from the exposed concrete surface. The outer layer of concrete in which an appreciable reaction with carbon dioxide has taken place is called the carbonated layer. Thus, the phenomenon of carbonation, which produces a denser surface layer with a so-called “clogged” pore system, reduces the absorptivity of the substrate concrete and might be expected to negatively affect bond strength.

Carbonation is generally a very slow process in good quality concrete, typically of the order of 1 mm per year. The rate of carbonation at ordinary temperatures is greater at relative humidities around 50% to 75%, although the relative humidity at which the maximum rate of carbonation is observed may be greater the higher the porosity of concrete.

Cracks, microcracks, or any other defects in the concrete allow carbon dioxide easy access through the concrete surface, and carbonation can occur. The active coefficient of carbon dioxide diffusion in a concrete crack, 0.008 inch (0.2 mm) wide is about three orders of magnitude (1,000 times) higher than in average-quality, crack free concrete [37].

Even though proper concrete removal and surface preparation operations usually remove carbonated concrete, relatively long periods of time between surface preparation and repair material placement may result in a new carbonation of the exposed substrate surface. Studies at Reclamation conducted as part of this program indicated that freshly sandblasted concrete surfaces can show signs of carbonation within a few hours.

Block and Porth [38] found in their studies that carbonated substrate did not affect the pull-off bond strength. Gulyas et al. [39], on the contrary, show that carbonation may decrease the bond strength significantly.

Test Program

Since the opinions of researchers on the effects of carbonation differ significantly, one of the tasks of the International Research Project was to conduct experiments to evaluate the effects of carbonated concrete surface on bond strength.

Testing for this part of the project was conducted by Reclamation. Eighteen 16- by 16- by 4-inch (400- by 400- by 100-mm) slabs were cast with 4,000-psi (28-MPa) concrete. Half of those slabs' top surfaces were prepared superficially for repair by sandblasting, while the other half were prepared by chipping hammer. In each group, four slabs were protected from carbonation (control), and five slabs underwent controlled carbonization in a laboratory carbonation chamber. The control slabs were protected with plastic sheet and duct tape to avoid carbonation. Slabs were undergoing carbonization for 2.5 months and reached a carbonation depth of greater than 3 mm (0.13 inch). The carbonated surface of the test slabs was then overlaid with 4-inch- (100-mm-) thick, 4,000-psi concrete. A total of nine pull-off bond tests were performed on each overlayed slab.

Conclusions

The effects of concrete substrate carbonation on the tensile bond strength for surfaces prepared by sandblasting and chipping techniques were investigated and analyzed. The following basic conclusions were drawn:

- For substrate surfaces prepared by sandblasting, there was no difference in bond strength found between carbonated and noncarbonated concrete surfaces.

- For substrate surfaces prepared by chipping, a significant reduction (16%) of bond strength was documented for carbonated surfaces compared to noncarbonated surfaces.

- Such different effects of carbonation were attributed to the possible microdefects (bruising) of the surface prepared by chipping hammer.

The limited number of tests performed using only one type of a repair material does not allow for conclusions about the overall effect of carbonation on the tensile bond strength. Different repair materials may not necessarily behave the same way in bond development to the carbonated surfaces. It is highly likely that carbonation may have only a slight impact on bond strength for an otherwise sound, properly prepared concrete substrate surface.

Recommendations for Further Research

Several fundamental aspects concerning concrete surface preparation prior to repair/overlay and bond strength development were addressed in this study. Although the results and analysis resulted in a better overall understanding of the problem, a number of questions remain unanswered. Studying the issues below would be the most effective way to provide more information to gain a better understanding to achieve optimum bond performance (strength and durability) in composite repair and overlay systems.

Effect of Moisture Conditioning of Concrete Substrate Upon Interfacial Bond in Repair/Overlay Systems

Despite the work accomplished in this project, some fundamental issues remain unresolved with regard to moisture conditioning of the concrete substrate prior to repair. In daily repair practice, inevitably loose specifications and the absence of measuring tools actually result in a wide range of moisture conditions.

In order to develop proper specifications, it is necessary to gain a better understanding of the transport mechanisms between repair materials and concrete substrates and the influence of the moisture state of the substrate upon bond development.

Both the issuing and implementation of such specifications will, in turn, require the development of a test method to evaluate quantitatively the actual moisture condition of concrete in the laboratory, as well as in the field. The envisioned method would allow the determination of optimum conditions for a given concrete substrate, as well as quality control testing. The method needs to be simple and applicable to both laboratory and in situ conditions. In that regard, further investigation should be directed towards measurement techniques already available, such as electrical impedance devices (flooring industry) or superficially encased relative humidity probes.

Long-Term Bond Properties Related to Different Repair/Overlay Materials, Interface Textures, and Environmental Conditions

It must be emphasized that this study, as well as other reported work on the subject, is primarily dealing with “short-term” bond strength issues, not with the mechanisms and issues related to long-term bond behavior and durability.

The short-term bond strength typically specified and evaluated can be used as an indication of the quality of workmanship (i.e., concrete surface preparation for repair, material selection, application, and curing).

Long-term bond strength, however, is usually influenced by various other factors, among them environmental, loading, and fatigue conditions.

Therefore, we recommend pursuing research efforts on those factors affecting long-term bond strength in concrete repair/overlay systems, notably the surface preparation parameters and characteristics.

Compatibility Issues in Composite Repair/Overlay Systems

When compatibility issues are properly addressed in repair systems, durability of the bond is achieved, as it ensures a lasting coexistence of the repair material and substrate concrete.

Incompatibility issues cause premature debonding and repair failures. Unfortunately, at the present time, much confusion, misconceptions, and misleading guidance exist concerning compatibility of repair materials and the substrate concrete. These issues negatively affect the design, specification, implementation, and, as a result, service life of concrete repairs and overlays.

Development of reliable guidelines addressing compatibility issues—with special emphasis on the factors related to dimensional compatibility issues—is needed for the repair industry to evolve as an engineering discipline.

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Appendix A

Suggested Guide Specification for Surface Preparation of Concrete Prior to Repair

About This Suggested Guide Specification

This document is intended to provide guidance on the surface preparation of concrete prior to repair and overlay. It can be used by individuals involved in developing project specifications who are competent to analyze the significance and limitations of these guide specifications' content and who will accept responsibility for the application of the material and provisions it contains.

This Suggested Guide Specification was developed for surface preparation of existing concrete for repair and overlay with Portland cement concrete and pre-packaged cement-based materials.

The document was developed based on the available results of the international research study "Development of Specifications and Performance Criteria for Surface Preparation Based on Issues Related to Bond Strength"[1], a review of best practices and the authors' knowledge of concrete repair.

This Suggested Guide Specification is preliminary because:

(a) some of the provisions are based partly on limited laboratory tests and theoretical analysis and should be further verified and correlated with field performance, including various service conditions (temperature, moisture, etc.);

(b) some of the criteria included need to be further assessed with regard to repeatability of test results;

(c) the effects of existing concrete substrates and repair materials variables need to be further researched and field evaluated.

Therefore, these Guide Specification should be modified by the results of further research and field trials.

Regarding further research, investigating different substrate concretes, interface textures and various repair materials would be helpful. In addition, further research will be necessary to develop a practical methodology for optimum moisture conditioning of the concrete substrate's surface prior to repair.

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1 General

1.1 Scope

These guide specifications contain recommendations for surface preparation of concrete prior to repair and overlay. The document summarizes current knowledge, best practices, and results of research concerning the surface preparation of concrete prior to application of repair/overlay materials. The guide specifications are applicable for repairing damaged or deteriorated concrete structures, correcting design or construction deficiencies, or upgrading a structure for new uses, or to meet more restrictive code requirements.

1.2 Intended Use

The specification details removal of concrete, preparation of the concrete substrate surfaces for repair and quality control/quality assurance for the work performed. These guide specifications are recommended for design engineers and construction professionals who face the task of introducing the best practices for concrete surface preparation to repair and rehabilitation projects.

These guide specifications are recommended for use after they have been properly adjusted to reflect specific site conditions and requirements and the user's specific expertise. For firms and agencies that already have guide specifications, it may be appropriate to incorporate portions of these specifications into their existing specifications.

Commentary

To achieve the goal of a durable repaired concrete structure use equipment, techniques and procedures that are appropriate for the project objectives, deterioration mechanism(s), environmental conditions, structural circumstances and other local conditions and limitations which exist for the specific structure or part of the structure under consideration.

Repair geometries, locations, access, amount and spacing of reinforcement, climatic conditions, available equipment, local engineering and labor skills, local and national regulations, etc. have to be considered and addressed in properly tailored concrete repair specifications.

1.3 Repair Guiding Principles

The success of concrete repairs is dependent on determining the cause and extent of concrete distress or deterioration, establishing realistic repair objectives, and developing a repair strategy to address repair needs. Typical steps for a systematic repair are as follows.

1.3.1 A condition survey, with a scope consistent with the perceived condition of the structure and the owner's repair objectives, performed by qualified individuals, to document and evaluate visible and non-visible defects and damage as well as potential damage.

1.3.2 An assessment of the application and service conditions to which the concrete repair is, or will be, exposed.

1.3.3 Determination of the cause of the damage or deterioration necessitating the repair; for example, mechanical damage such as impact or abrasion; design, detailing or construction deficiencies; chemical damage, such as alkali-aggregate reaction; physical damage related to cycle of freezing and thawing or thermal movements; and corrosion of steel reinforcement caused by improper placement, carbonation of concrete, or chloride ingress into the concrete.

1.3.4 Determination of the repair objectives, including desired service; and durability planning including service life modeling.

1.3.5 Design of a repair project including appropriate specifications for a specific project.

1.3.6 In the specific repair project, the specifier should consider outside constraints such as limited access to the structure, the operating schedule of the structure, any limitation imposed by the owner of the structure, including the cost, and the required useful life of the repaired structure.

1.3.7 Consideration should also be given to the physical, chemical and electrochemical condition of the existing concrete substrate, the ability of the structure to carry loads, movement and vibration during repair, ambient conditions, and the characteristics of substrate materials and those of the repair materials and systems.

1.3.8 Safety and structural stability before, during and after the repair should be maintained in accordance with the specific project specifications and design.

1.4 General Requirements

The following requirements should be met.

1.4.1. The achievement of the required condition of the substrate regarding cleanliness, roughness, cracking, tensile and compressive strength, chlorides content and other aggressive agents, depth of carbonation, moisture content and temperature.

1.4.2 The achievement of the compatibility of the existing concrete and reinforcement with the repair and protection materials and systems, and compatibility between different repair and protection products, including avoiding the risk of creating conditions which may cause acceleration of corrosion or acceleration of other deterioration mechanism.

1.4.3 The achievement of the specified requirements, characteristics and properties of repair materials and systems and the composite repair system regarding the fulfillment of their purpose to prolong the useful service life of the structure.

1.4.4 The achievement of the required repair application conditions of ambient and substrate temperature, humidity, wind force, precipitation and any temporary protection when needed.

1.5 Commentaries

This Suggested Guide Specification provides commentaries with background information to the normative text to facilitate specific requirements and decisions when particular project specifications are prepared.

2. Concrete Removal

2.1 Description

2.1.1 This section specifies procedures, equipment and requirements for the removal of concrete in areas designated for repair.

2.1.2 The process of concrete preparation for repair is the process by which sound, clean, and suitably roughened surfaces are produced on concrete substrates. This process includes the removal of unsound and, if necessary, sound concrete and bond inhibiting foreign materials from the concrete and reinforcement surfaces, opening the concrete pore structure, and preparation and repair of damaged reinforcement that may be present.

2.1.3 Unsound or deteriorated concrete is defined as: concrete affected by weakness, spalling, delamination, cracking, disintegration, and concrete in areas with cracking due to corrosion of reinforcing steel.

2.1.4 "Unsound" concrete suggests that the material is in a reduced physical condition and hence is usually relatively easy to remove. Alternatively "sound" concrete in all probability may be in physically good condition and involves considerable effort for its removal. Concrete contaminated with chlorides and/or carbonated concrete can be and usually is physically sound concrete.

2.1.5 Concrete removal usually involves unsound material. However, some sound concrete is also removed to permit for adequate repair geometry, to remove contaminated concrete, to prepare embedded reinforcement, and to permit structural modifications. The effectiveness of various concrete removal techniques may differ for unsound and sound concrete and a combination of techniques may be necessary.

Commentary

Proper attention to surface preparation is essential for a durable repair. Regardless of the cost, complexity and quality of the repair material and application method selected, the care with which concrete is removed and concrete reinforcement surfaces are prepared will often control whether a repair project will be successful.

2.1.6 Do not use methods to remove concrete or to prepare the concrete and reinforcement to receive the repair material that weakens the remaining sound concrete and reinforcement.

2.2 Structural Safety

2.2.1 Review the effect of concrete removal on the structural integrity of a structure prior to removal of existing concrete. Provide temporary shoring in cases where removal of concrete and/or reinforcing steel can affect the load carrying capacity of the structure or its elements. Caution needs to be exercised in order that the safety of the structure is not jeopardized by repair activities.

2.2.2 Review details of shoring to be used that are designed and stamped by a Professional Engineer. However, the Contractor is responsible for the safety and adequacy of the shoring system.

2.2.3 The limitations for concrete removal such as the depth, reduction of cross section, the amount of concrete removed from the top surface, etc. are subjected to the restrictions described in the contract.

2.3 Precautions Prior to Concrete Removal

2.3.1 Examine areas where concrete is to be removed to determine if there are electrical conduits, utility lines, or other embedments in the concrete which may be damaged during removal.

2.3.2 f required, enclose work areas with a barrier suitable to confine dust and debris inside the work areas. Inspect the enclosures to ensure they are securely constructed and inspect the enclosure each working day to ensure that there are no holes or tears.

2.3.3 Ensure that the level of equipment exhaust fumes (such as from air compressors or portable generators) is within acceptable limits. Use equipment and locate the equipment so that the fumes can be properly exhausted away from occupied areas.

2.3.4 Ensure that dust and debris does not constitute a hazard to personnel, equipment, the structure, its occupants and the general public. Keep dust and debris away from the working area by continuous cleaning.

2.4 Concrete Removal Geometry

2.4.1 The location, number, and extent of defects shown in the Contract are indicative only. The true location, number, and extent of defects requiring repair can only be assessed properly by close inspection and other testing during the course of concrete removal. Mark the limits of each repair with chalk or paint as a series of straight lines on the surface. The limits of each shall be approved by the Engineer before removal begins.

Commentary

Modify areas requiring repair to provide for simple layouts. Design the layouts to reduce boundary edge length and eliminate acute angles. Excessive or complex edge conditions are usually produced by trying to closely follow the shape of the deteriorated concrete. Such edge conditions often result in shrinkage stress concentrations and cracking.

2.4.2 Make right angle cuts to the concrete surface by saw cutting, chipping, grinding or hydrodemolition at the perimeters of repairs that involve concrete removal.

2.4.3 Measure and record on drawings the extent and depth of concrete removal required. Obtain approval from the Engineer as the work proceeds.

2.5 Saw Cutting

2.5.1 Make saw cut along the perimeter of the area where concrete is to be removed to reduce edge spalling and to provide a sound edge surface against which the repair material will be placed.

2.5.2 Make the saw cuts as deep as practical and to a minimum depth of 1 inch (13 mm). Adjust or eliminate saw cutting to prevent damage to embedments. If necessary, use a grinder to create a minimum ¼-inch face perpendicular to the repair surface in areas that cannot be saw cut (see 2.7). Roughen saw cuts prior to application of the repair material. This can be accomplished by sand blasting at the same time as cleaning of exposed reinforcement. Care needs to be exercised when roughening the cut surfaces to avoid damage to the repair cavity edges.

2.5.3 Use water-wash equipment to remove sawing slurry from the repair area before it dries.

Commentary

The advantages of creating a face perpendicular to the repair surface by saw cutting include the following:

- *Repair material can be consolidated more effectively with less concern for moving repair material out of the repair – the squared edges help contain the repair material;*
- *The forces experienced by the concrete during chipping are isolated within the sawed boundaries;*
- *Very little spalling of the remaining concrete occurs;*

- *Removing concrete within the sawed boundaries is usually easier and faster when the boundaries are sawed than when they are not;*

- *Most crews are familiar with the method.*

- *The disadvantages of the saw cutting procedure include the following:*

- *More workers are required than in the other procedures;*

- *Since water is often used when sawing, the repair area is saturated for some time, possibly delaying the repair;*

- *Saw overcuts weaken the repair area and must be cleaned and sealed or preferably, not allowed;*

- *The polished, vertical repair boundary faces may lead to poor bonding*

2.6 Chip Cutting

2.6.1 This method will only be allowed under special circumstances.

2.6.2 The boundaries in the chip cutting procedure are the same as in the saw cut procedure, except the repair boundaries are not sawed. The concrete in the center of the repair area is removed using a light jackhammer with a maximum weight of 15 lb (6.8 kg). The concrete near the repair borders is then removed using a light jackhammer with a maximum weight of 15 lb (6.8 kg) and hand tools. The work should progress from the inside of the repair toward the edges, and the chisel point should be directed toward the inside of the repair.

Commentary

The advantages of the chip cutting procedure are primarily economic and include the following:

- *There are no saw overcuts;*
- *It has fewer steps than the saw cut method;*
- *The rough vertical edge produced promotes bonding;*
- *Spalling is controlled by using light hammers at the edges.*

The chip and patch procedure may be faster because it has fewer steps; the patch boundaries are not sawed, and there are no saw overcuts to be cleaned and sealed. If saws are used for joint sawing, after that is *completed the saw is not needed again, even if more unsound concrete is later found beyond the boundaries.*

The disadvantages of the chip cutting procedure include the following:

- *Sound concrete may be damaged by chipping hammers;*
- *Hammers can cause feathered patch edges;*
- *Vertical sides are difficult to achieve.*

2.7 Edge Grinding

2.7.1 This method will only be allowed under special circumstances.

2.7.2 The boundaries in the edge grinding procedure are the same as in the saw cut procedure, except the repair boundaries are not as deep. Make grind cuts along the perimeter of the area where concrete is to be removed to reduce edge spalling and to provide a sound edge surface against which the repair material will be placed.

2.7.3 Make the grind cuts as deep as practical and to a minimum depth of approximately 1/4 inch (3 mm). Roughen ground surfaces prior to application of the repair material. This can be accomplished by sand blasting at the same time as cleaning of exposed reinforcement. Care needs to be exercised when roughening the ground surfaces to avoid damage to the repair cavity edges.

Commentary

The advantages of creating a face perpendicular to the repair surface by edge grinding include the following:

- *Repair material can be consolidated more effectively with less concern for moving repair material out of the repair – the squared edges help contain the repair material;*

- *The forces experienced by the concrete during chipping are isolated within ground boundaries;*

- *Very little spalling of the remaining concrete occurs;*

- *Removing concrete within the boundaries is usually easier and faster when the boundaries are ground than when they are not;*

- *Most crews are familiar with the method.*

The disadvantages of edge grinding procedure include the following:

- *More workers are required than in the other procedures;*
- *Since water may be used when grinding, the repair area is saturated for some time, possibly delaying the repair;*
- *Grinding overcuts weaken the repair area and must be cleaned and sealed, or preferably, not allowed;*
- *The polished, vertical repair boundary faces may lead to poor bonding.*

2.8 Concrete Removal Methods

2.8.1 General

Concrete removal methods are categorized by the way in which the process acts on concrete. The general categories are impacting, blasting, cutting, milling, pre-splitting, and abrading. ACI 546R[2], Concrete Repair Guide, provides a description of these categories, lists the specific removal techniques, and provides a summary of information on each technique.

Only impacting and hydrodemolition (waterblasting, water jetting) concrete removal methods are addressed in this section.

2.8.2 Impacting Methods

2.8.2.1 General

Impacting methods are the most commonly used concrete removal systems. They generally employ the repeated striking of a concrete surface with a high energy tool to fracture and spall the concrete. Impacting methods include hand-held breakers and scabblers.

In most applications, scabblers are not permitted. In addition, bush heads should not be used on hand held breakers and chipping hammers

2.8.2.2 Hand-held breakers

The hand-held breaker or chipping hammer is probably the best known of all concrete removal devices. Hand-held breakers are available in various sizes with different levels of energy and efficiency. The smaller hand-held breakers (15 pounds) are commonly specified for use in partial removal of concrete or concrete around reinforcing steel, because they do little damage to surrounding concrete. The larger hand-held breakers (30-90 pounds) are used for complete removal of large volumes of concrete. Exercise care when selecting the size of breakers to minimize the damage to existing concrete and its bond to embedded reinforcing steel.

Commentary

Chipping hammers are typically classified by weight, even though breakers of similar weight do not necessarily generate the same impact force.

The percussive force used by pneumatic breakers to fracture concrete is primarily determined by the impact energy and the frequency at which the impacts occur. The impact energy is based on the mass of the piston, the size of the cylinder, and the inlet port diameter. Impact energy ranges from approximately 15 lb (6.8 kg) per blow for small tools to more than 180 lb (82 kg) per blow for large tools. The frequency of impact, or blows per minute, ranges from 900 blows per minute to more than 2,000 blows per minute, depending on the valve design.

Various cutting tools are available for use with hand-held pneumatic breakers. The shank end, which is inserted into the tool-retaining mechanism, is common to all. The cutting or working end can vary from a broad spade like blade to a sharp well-honed point. The vast majority of concrete removal work is done with a pointed tool, although a relatively narrow (3 in. to 4 in. [7.5 cm to 10 cm]) blade-type tool is sometimes used to remove cracked and deteriorated concrete.

2.8.2.3 Environmental Concerns

Effects of the breaker concrete removal operation must be monitored to ensure minimal impact on the surrounding environment. The primary issues of concern are noise, dust, and flying debris.

2.8.2.4 Concrete Removal Procedure

The first step in the removal procedure is usually saw cutting the repair are boundaries. The deteriorated concrete in the center of the repair is then removed using a light jackhammer with a maximum weight of 15 lb (6.8 kg). The work should progress from the inside of the repair toward the edges. When all unsound concrete in the repair area is removed and repair geometry is established the final procedure is to remove the concrete near the repair borders using a light jackhammer and/or hand tools.

Removal near the repair boundaries must be completed with hammers fitted with spade bits as gouge bits can damage sound concrete. Jackhammers and mechanical chipping tools should be operated at an angle less than 45 degrees from the vertical.

2.8.3 Hydrodemolition

2.8.3.1 Hydrodemolition (also called water jetting or waterblasting, see section 3.2.4) procedures use a high pressure water jet to remove concrete. A high-pressure and ultra high pressure water jet uses a small jet of water driven at high velocities commonly producing pressure of 10,000 to 45,000 psi (70 MPa to 310 MPa) and above. Lower pressures can usually be used to clean concrete surfaces that have already been prepared using impacting concrete removal methods.

Commentary

Pressures from hydrodemolition used for concrete removal and surface preparation can be defined as follows:

Low: Maximum 5000 psi (35 MPa)

High: Between 5000 psi and 20,000 psi (35 MPa to 140 MPa)

Ultra high: Between 20,000 psi and 45,000 psi (140 MPa to 310 MPa)

Although hydrodemolition will not physically damage steel tendons, it is not considered to be a viable concrete removal technique if there is a possibility of the high- pressure water coming into contact with tendons, anchorages, or both. Reasons why hydrodemolition is not considered to be a viable technique in these cases include:

a) Hydrodemolition of post-tensioned concrete elements may cause a safety problem. It is potentially dangerous because it may undercut embedded anchors and result in explosive release of prestressing force.

b) If any part of the tendon is exposed to high water pressure, water may penetrate into the tendon. The water jets will likely destroy the sheathing on the tendons, whether it is wrapped in paper, plastic, tubing, or extruded plastic. If the sheathing is damaged, the water has a direct path to the prestressing strand or wire, and corrosion may result.

c) *Concrete repair projects commonly include replacement of post-tensioning strand. The water pressure used in hydrodemolition equipment can force slurry into the sheathing. When slurry and other debris exist within the sheathing, installation of a new strand becomes very difficult. When the new strand is pushed into the existing sheathing, debris within the sheathing builds up ahead of the advancing strand. This buildup of debris can cause the sheathing to rip and "ball up" in front of the leading edge of the strand. This scenario makes strand replacement very difficult and compromises the corrosion protection or sheathing over the prestressing steel.*

More information can be found in ACI 423.4R[3].

2.8.3.2 Hydrodemolition may be used as a primary means for removal of concrete when it is desired to preserve and clean the steel reinforcement for reuse and to minimize damage to the concrete remaining in place. Hydrodemolition disintegrates concrete, returning it to sand and gravel-sized pieces. This process works preferentially on unsound or deteriorated concrete and leaves a rough profile.

Commentary

In some cases, care must be taken not to punch through slabs or decks if unsound concrete extends deeper than expected.

High-pressure water jets in the 10,000 psi (70 MPa) range require 35 to 40 gal/min (130 to 150 L/min). As the pressure increases to 15,000 to 20,000 psi (100 to 140 MPa) the water demand will vary from 20 to 40 gal/min (75 to 150 L/min). The equipment manufacturer should be consulted to confirm the water demand. Ultra-high-pressure equipment operating at 20,000 to 35,000 psi (170 to 240 MPa) has the capability of milling concrete to depths of ⅛ inch to several inches (3 mm to approximately 50 mm).

2.8.3.3 Hydrodemolition should not be allowed for concrete removal if there is a possibility that unbonded post-tensioned systems are within the concrete removal zone. The only viable method of concrete removal in this situation is concrete removal using lightweight chipping hammers.

2.8.3.4 Two trial areas, one of sound concrete and one of deteriorated concrete, are used to determine the appropriate hydrodemolition operating parameters. These parameters include speed, pressure, and the number of overlapping passes. Using trial and error in the test areas, the hydrodemolition machine must be programmed to prevent removing sound concrete unnecessarily. In the sound area, consistent concrete removal depth to the prescribed clear space behind the reinforcing bar shall be obtained as a minimum. After successful cutting of the test area, with specified depth control, the operation shall be moved to the deteriorated concrete, and a test performed to remove all deteriorated concrete. If a result is obtained which meets the specified requirements, these parameters shall be used as a basis for the production removal. If not, the Contractor shall repeat the trial process and recalibrate or replace the equipment until a result which meets the specified requirements is obtained. Once properly calibrated, the operating parameters should not be changed during hydrodemolition of the deteriorated concrete, unless the concrete changes (for example, a harder aggregate has been used in one section of the structure). If the concrete does change, the hydrodemolition machine must be recalibrated.

2.8.3.5 All concrete within a marked repair area should be removed to a minimum depth of 2 in (51 mm) with neat vertical faces. Then the repair area must be tested again for soundness. Any additional unsound concrete must be removed by continued hydrodemolition.

Commentary

The debris and slurry that result from the hydrodemolition operation must be removed before the slurry dries and hardens on the surface of the cavity. If this is not done, the dried slurry can be hard to remove. Sandblasting or high pressure water cleaning may or may not be able to remove the dried slurry residue.

Some moisture-sensitive materials may require that the repair area be completely dry before placing the material.

The advantages of hydrodemolition include the following:

- *It requires fewer workers than the other procedures;*
- *Once an experienced operator adjusts the operating parameters, only weak concrete is removed;*
- *The cavity surfaces produced are vertical, rough, and irregular, and enhance bonding;*
- *Concrete around reinforcing can be relatively easily removed with the same or similar equipment.*

The disadvantages of hydrodemolition include the following:

- *The finished surfaces are saturated. Placement must be delayed until the area dries unless the repair material is not moisture-sensitive;*

- *The fine slurry laitance remaining after the procedure must be removed before it dries on the surface;*

- *A protective shield must be built around the repair area if it is next to occupied areas;*

- *It can be difficult to control the depth of removal;*

- *Equipment is expensive;*

- *It can be difficult to obtain a good production rate; performance of hydrodemolition equipment has been variable;*

- *For large jobs, an ample source of relatively clean water is needed;*

- *The waste water and debris must be handled in an environmentally acceptable manner as prescribed by local regulations.*

2.9 Concrete Removal Depth

2.9.1 Remove all unsound concrete. If during the removal operation, reinforcing steel is exposed, then remove concrete around the bar to provide a minimum ¾ inch clear space between the rebar and surrounding concrete or a clear space of ¼ inch larger than the maximum size aggregate in the repair material, whichever is greater.

2.9.2 Remove concrete to a minimum depth suitable for the selected concrete repair material. Some materials may require more concrete removal than removal depth required for removal of damaged concrete.

2.10 Treatment of Reinforcing Steel

2.10.1 Nationally, the most frequent cause of concrete deterioration is the corrosion of embedded reinforcing steel. Proper evaluation of the condition of reinforcing steel exposed in the repair area and proper reinforcement treatment steps will ensure that the repair will not fail prematurely.

2.10.2 The first step in preparing reinforcing steel for repair or cleaning is the removal of deteriorated concrete or chloride contaminated concrete surrounding the reinforcement. Extreme care should be exercised to insure that further damage to the reinforcing or prestressing steel is not caused by the process of removing concrete. Impact breakers can damage reinforcing steel if the breaker is used without regard to the location of the reinforcement. Once the larger areas of unsound concrete have been removed, a smaller chipping hammer (15 lbs.) should be used to remove the concrete in the vicinity of the reinforcement. Care should be taken not to vibrate the reinforcement or otherwise cause damage to its bond to concrete adjacent to the repair area.

2.10.3 Perform additional concrete removal along corroded exposed bars until a continuous length of 2 in (50 mm) of bar free from corrosion is exposed. Assessing the limit of active corrosion shall be on a visual basis. The edges of any additional areas removed shall be cut square as specified above. The extent of concrete removal shall be agreed to by the Engineer before any removal commences.

2.10.4 An additional length of uncorroded bar will have to be exposed if couplers or lap splices are to be used for replacement reinforcement.

2.11 Concrete Surface Roughness

2.11.1 Substrate roughness depends to a large extent on the method of substrate surface preparation. Mechanical methods of concrete removal normally leave the substrate surface much rougher than abrasive blast methods. The magnitude of surface roughness for concrete repairs is commonly measured in millimeters (mm) or inches (in).

2.11.2 Unacceptably rough or flat substrate profiles after concrete removal may be reduced through additional work using properly selected surface preparation techniques.

2.11.3 The decisions about surface preparation, and its roughness in particular, cannot be made without knowing the properties and application requirements of the selected repair/overlay material. If a prepackaged repair material is selected for use, consult the material manufacturer.

2.11.4 For selecting, specifying and evaluating the concrete surface profile follow the International Concrete Repair Institute (ICRI) Guideline No. ICRI 310.2-1997[4]

The nine concrete surface profile (CSP) chips provide benchmark profiles to aid in achieving the desired results. Each profile carries a number ranging from a base line of 1 (typically designated as CSP-1 which is nearly flat) through 9 (CSP-9, very rough).

Commentary

There are numerous profile evaluation methods available, but unfortunately most of them are not applicable for practical field purposes.

The most widespread test method currently used to characterize surface roughness is the International Concrete Repair Institute (ICRI) Guideline No. ICRI 310.2-1997[4]. However this method is presently limited to a roughness of about ¼ in (6 mm) only.

A more precise method, but less practical for in-situ application is the ASTM E965 "Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique"[5] sand spread method in which sand of known volume is spread over the concrete surface to form a circle until all sand has settled in the surface cavities. The roughness is then calculated from the diameter of the circle.

3. Concrete Substrate Surface Conditioning

3.1 General

3.1.1 This section addresses the final concrete surface and reinforcing steel preparation steps after concrete removal and prior to application of the repair material.

The preparation of the substrate for repair has to be suitable for the required condition of the substrate and the structural and safety status of the structure to be repaired, so that the realistic requirements of the completed repair, as specified, are satisfied.

Commentary

In all repair types it is important that the new repair adheres well to the substrate concrete. In this respect, it is important that preparation of the concrete surfaces to receive the repair materials be given careful attention as the adhesion developed is as dependent on good surface preparation as on repair material characteristics. Clearly efforts to obtain good adhesion to a weak surface are futile since failure of the concrete surface is likely to occur. Conversely poor adhesion to a sound surface is possible if the surface is inappropriately prepared.

3.1.2 For a successful repair, the following conditions must be satisfied:

a) The concrete must be strong and sound;

b) The surface should receive the optimum moisture conditioning;

c) The surface should be free of dust, laitance or any other foreign materials;

d) The surface should have an open pore system;

e) The surface temperature should be within suitable limits to permit proper wetting by the repair materials.

3.1.3 Place repair materials as soon as possible after concrete removal and cleaning is completed or protect the cleaned and prepared concrete and reinforcement surfaces from contamination.

3.2 Surface Cleaning

3.2.1 Concrete removal methods may leave the surface to receive the repair material too smooth, too rough, too irregular, and without open pores. In these cases, procedures specifically intended for surface cleaning are necessary.

Microcracking (sometimes called bruising) of the concrete surface is common when impact tools are used to remove concrete. A surface with bruising may weaken the bond between the existing concrete and the repair. In this case, a less aggressive method of surface preparation such as abrasive or waterblasting is necessary.

Concrete can be removed by a variety of methods such as chipping hammers, abrasive blasting, and hydrodemolition. Removal subjects the concrete substrate to a wide range of dynamic loads, and the resulting bruising will depend on the method used and the quality of the concrete. The depth of the bruised layer varies, but is typically on the order of ⅛ in. (3.0 mm). There are no criteria for the degree of bruising that reduces service life.

Pull-off testing of the repair system (surface repair and substrate) can be conducted to determine the bond strength. Excessive bruising may result in low pull-off strength with the failure surface running entirely through the substrate. Bruising is identified conclusively by microscopic examination of the concrete. This examination is typically performed on small samples by a concrete petrographer to identify severity of microcracking. To see bruising, a polished surface needs to be magnified 20 to 100 times, depending on the width of the cracks.

Bruising can be minimized by exercising care in the removal process and by avoiding techniques that experience has shown to cause bruising. Techniques to avoid include the use of scabblers, scarifiers, bush hammers, or large pneumatic hammers, especially those equipped with wide chisel tools.

Bruising can be minimized by using methods such as abrasive sand, shot- or water-blasting, or hydrodemolition. Where the more damaging methods must be used to increase production or reduce costs, the damage can be mitigated somewhat by abrasive sand, shot- or water-blasting as a final preparation step for the final 0.10 in. Replacing the commonly used sand in abrasive blasting with alternative materials such as sintered slag, flint silicon carbide, or aluminum oxide can reduce damage.

The use of lightweight pneumatic-chipping hammers equipped with sharp, pointed tools can also reduce the magnitude of bruising.

3.2.2 First stage cleaning operations shall be commenced in a repair area after all necessary concrete removal has been completed. The remaining concrete surface must have laitance, partially loosened chips of concrete and the bruised concrete layer, removed by blasting.

3.2.3 Second Stage Blasting and Cleaning

If in the Engineer's opinion bruising and/or contaminants, or weathered and carbonated concrete surface, which might interfere with bond, are present on the prepared surface, second stage blasting and cleaning must be performed as directed by the Engineer prior to placement of the repair material.

Commentary

The old weathered and carbonated concrete surface is usually removed during concrete removal operations and following first stage cleaning. However, long periods of time between these operations and repair material placement may result in new carbonation of the exposed surface.

The issue of effect of carbonated surface on bond strength is quite controversial. Some investigations show that carbonation may decrease the bond strength significantly, and others, on the contrary, found that substrate carbonation does not affect pull-off bond strength. Theoretical analysis, however, leads to the opinion that carbonation does affect the bond strength since it not only densifies the affected concrete, but also changes the pore structure. The effect of carbonation on bond durability is not known.

Therefore, if excessive time passes after concrete removal and cleaning before repair material placement is performed, additional cleaning to remove the carbonated surface is justified.

3.2.4 Cleaning Techniques

These techniques consist of removing thin layers of surface concrete using abrasive equipment such as sandblasters, shotblasters, or high-pressure waterblasters. Abrading techniques remove concrete by propelling an abrasive medium at high velocity against the concrete surface to abrade it as a final step in surface preparation. The process uses common abrasive medium as a primary abrading tool. The process may be executed in one of three following methods.

Sandblasting — Sand blasting is the most commonly used method of cleaning concrete and reinforcing steel. The process uses common sand, silica sand, metallic sand or slag (Black Beauty) as the primary abrading agent.

Shotblasting — Shotblasting equipment cleans concrete by projecting metal shot at the concrete surface at a high velocity. This equipment has the capability to remove finite amounts of sound or unsound concrete. The shot erodes the concrete from the surface. The shot rebounds with the pulverized concrete and is vacuumed into the shotblasting machine. The concrete particulates are separated out and deposited into a holding container to be discarded later while the shot is reused. The shotblasting process is a self-contained operation that is highly efficient and environmentally sound.

Waterblasting — Water is sprayed at pressures between 5,000 and 15,000 psi (35-105 MPa). This technique is suitable for vertical and horizontal surface cleaning. It is the largely the same as hydrodemolition, except that smaller and hand held equipment is typically used.

Waterblasting (with abrasive) — Water blasting with abrasives is a cleaning system using a stream of water at high pressure with an abrasive such as, aluminum oxide, or garnet introduced into the stream. This equipment has the capability of removing dirt or other foreign particles as well as concrete laitance thereby exposing the fine aggregate.

3.2.5 Reinforcement Cleaning, Inspection and Repair

3.2.5.1 The initial cleaning of exposed reinforcement is usually achieved during the concrete surface cleaning procedures using blasting techniques.

3.2.5.2 After the initial cleaning, reinforcing steel shall be carefully inspected to determine whether the steel shall be cleaned or repaired. The objective of the inspection is to determine whether the reinforcing steel is capable of performing as intended by the design. If the cross-section area of the rebar has been reduced by corrosion by more than 25 percent, the Engineer shall make the decision on the actions to be taken. One of three options may be taken:

a) To do nothing;
b) Add supplemental reinforcement;
c) Replacement.

3.2.5.3 Supplemental Reinforcement

This alternative is selected when the reinforcing steel has lost cross section, the original reinforcing was inadequate, or the existing member is to be strengthened. The decision to add supplemental reinforcing steel is the responsibility of the Engineer. Methods of supplementing reinforcement are as follows:

a) Extra reinforcement using straight laps. The concrete should be chipped away to allow placement of the supplemental bar beside the existing bar. The length of the supplemental bar should be equal to the length of the damaged segment of the existing bar plus a lap splice length on each end equal to the lap splice requirements for the smaller bar diameter of the two as specified in the applicable code.

b) Anchored extra reinforcement. Extra reinforcement may be installed with reduced laps by anchoring the ends at 90° to the concrete face. The ends should be embedded using resin or cementitious mortars. Care must be taken to avoid damaging adjacent areas where the existing reinforcement to concrete bond remains intact.

3.2.5.4 Replacement

The method of replacing reinforcement is to cut out the damaged portion and splice in replacement bar. If possible, a conventional lap splice shall be used. When lap splices are not applicable, welded splices or approved mechanical connectors in the form of threaded couplers or bar grips shall be used.

A welded connection, if used, shall require submittal by the Contractor and approval by the Engineer of a welding procedure along with the test results to demonstrate the strength of the welded joint and metallurgical compatibility of the weld material with the reinforcing steel.

Commentary

The site welding of reinforcement should be avoided if alternative methods of repair are available. Doubts remain as to whether the welded sections can restore the strength properties of the original undamaged bar. The introduction of heat or preheating may induce thermal stresses on cooling and could damage the bond between the existing reinforcement and concrete substrate.

3.2.6 Corrosion Protection

3.2.6.1 When epoxy-coated steel reinforcement is exposed in the repair area it should be recoated with an epoxy coating. Special care must be exercised during the recoating operation to achieve defect free full surface coverage. Uncoated spots may result in severe corrosion in repair areas.

3.2.6.2 When uncoated reinforcing steel is exposed in the repair area application of a protective coating should not be done, because it may cause corrosion in areas immediately adjacent to the repair area.

3.2.6.3 Repairs of corrosion related concrete deterioration are usually performed in the areas where the corrosion activity is at its worst – at "hot spots." After these areas are repaired, the "hot spots" can move to the areas adjacent to repair areas. To protect such areas, consideration of the use of sacrificial galvanic anodes should be made in accordance with the manufacturer's recommendations.

Commentary

A commonly observed phenomenon in concrete repair is increased corrosion activity in existing concrete areas immediately adjacent to a repair. This effect has been referred to as the anodic ring effect, the incipient anode effect, and the halo effect. The repair of corrosion-affected concrete usually addresses the areas where the corrosion activity and related damage is worst – sometimes referred to as the "hot spot". In many cases, it is likely that the conditions in surrounding areas are such that corrosion can occur, however, corrosion activity in these areas has been reduced or dormant due to the active corrosion occurring at the hot spot. This reduction is a form of cathodic protection provided by the hot spot. When the repair is completed, the hot spot has been removed, and the adjacent areas are no longer being cathodically protected. In such cases the repair area can contribute to corrosion in the adjacent, non-repaired areas. The result is a new "hot-spot" which may require additional repair in three to five years.

3.2.6.4 To neutralize or slow down new corrosion cells, which would otherwise develop around the repaired area, embedded galvanic anodes can be installed following manufacturer's recommendations.

Commentary

Based upon many of the same principles used for protecting pipelines and ships from corrosion, these anodes are "sacrificial" in nature.

The galvanic principle behind its operation is quite straightforward. Since the sacrificial anode (zinc), is more reactive than the reinforcing steel to which it is connected, the zinc anode will corrode preferentially to the reinforcing steel. As the zinc corrodes, it releases electrons into the surrounding reinforcement to reduce corrosion activity on the steel.

Proper cleaning of the rebar helps to assure the anode tie wires are able to make a good electrical connection. Since the anodes function on electrochemical principles, maintaining low resistance connections ensures peak performance.

The location of the anodes within the repair area is another key to proper performance. By definition, ring anode corrosion will develop in *close proximity to the repair area. Therefore, the anodes should be placed as close as is practical to the edge of the repair to provide the greatest protection to the surrounding concrete. For this reason anodes are generally not necessary within the interior of the repair. Instead of fastening anodes throughout the repair, the ring-anode effect may be mitigated by simply installing anodes around the perimeter of the repair at the appropriate spacing. Such a feature allows the anodes to be used sparingly – only in the areas that require protection.*

3.3 Moisture Conditioning of the Concrete Substrate

3.3.1 General

Factors that influence the formation of a bond between a repair material and a prepared substrate include: the properties of the substrate concrete and its surface, the properties of the repair material, absorption, adhesion, and environmental conditions. Several of these factors are critically dependent on moisture condition of the substrate prior to application of repair materials.

The optimum moisture condition will vary from substrate to substrate in otherwise equal conditions. Among many factors, the performance of the bond will also depend on the way the substrate and repair material interact relative to the direction and rate of water and cement paste movement between the repair material and the substrate material.

Commentary

The moisture condition of the substrate will determine the rate of movement of water from the repair mortar to substrate concrete due to the moisture imbalance between the two layers. Both the surface moisture condition and the moisture distribution inside the substrate are important. During the process of water movement, water can move out of or into the repair material, and may penetrate into the capillaries of the substrate concrete. Hydration of the cement paste in the repair material can also impact water movement.

3.3.2 The optimum water condition of a concrete substrate for a particular cement-based repair material can be determined by preliminary testing using different moisture surface conditioning:

a) Saturated Surface Dry (SSD)
b) Saturated Surface Wet (SSW)
c) Unsaturated Surface Dry (USD)
d) Unsaturated Surface Wet (USW)

3.3.3 In cases when such testing cannot be performed, SSD moisture conditioning should be applied. Under this condition the substrate looks damp but contains no free water on the surface. The surface absorbed all the moisture possible but does not contribute water to the repair material mixture.

Commentary

The recommended experimental method of evaluating the optimum moisture conditioning of a specific concrete substrate and specific repair material(s) utilizing four various moisture conditions is a relatively labor and time consuming alternative. It can only be effectively implemented on large repair/overlay projects.

The saturated surface dry (SSD) condition is not always the best choice, but when experimental evaluation of the optimum moisture condition is not conducted, is a "safe" compromise.

The SSD condition is a very subjective surface moisture quantity. For example, how deep should the saturation be? And how do you measure that?

Unfortunately, a reliable, user-friendly methodology for relatively easy evaluation of the optimum moisture condition of a given concrete substrate presently is not available.

3.4 Maintenance of the Prepared Surface

3.4.1 After the substrate has been prepared, it should be maintained in a clean condition and protected from damage until the repair/overlay material is placed.

Prepared areas should be protected from repair activities in adjacent areas. Mud, debris, cement, dust, etc., when deposited on a prepared surface, will act as a bond breaker if not cleaned up before the repair material is placed.

3.4.2 In hot climates shade should be provided, if practically possible, to keep the substrate cool, thereby reducing rapid hydration or hardening of repair materials. In wintertime, necessary steps should be taken to provide sufficient insulation and/or heat to prevent the repair area from being covered with snow, ice, or snowmelt water.

3.5 Quality Control of Surface Preparation

3.5.1 The integrity and ultimate performance of repairs and overlays is in large part determined by the quality of the existing concrete surface preparation. It is imperative that care be taken, specifications followed, and surface preparation quality control and related decisions be made by qualified personnel.

3.5.2 Qualified personnel are required for all testing and inspection operations, and shall be performed by the Engineer's representative, and not by the Contractor performing the surface preparation.

3.5.3 The direct tension test of existing concrete should be performed as a part of condition evaluation program to allow the specifier to establish the realistic bond strength requirements.

3.5.4 To provide assurance that the surface preparation procedures were performed as specified, the tensile pull-off tests shall be performed on the prepared surface prior to repair application. The pull-off test should be done in accordance with the applicable provisions of the ICRI Guideline No. 210.3-2004 (formerly 03739), "Guide to Using In-Situ Tensile Pull-Off Tests to Evaluate Bond of Concrete Surface Materials[6]."

3.5.5 In case when the tensile strength of the prepared substrate tested significantly deviates from the tensile strength of the existing concrete documented in the condition evaluation report, the data shall be analyzed by the Engineers, and additional surface treatments may be necessary.

Commentary

Many specified testing criteria for bond strength of completed overlays and surface repairs are based on documented recommendations of ACI and ICRI, and seldom on considerations related to the actual strength of the given concrete to be repaired. In cases when such criteria is not being met based on the tensile pull-off test results of the completed repair or overlay, it is very difficult to establish what went wrong: surface preparation, repair material quality, workmanship, environmental conditions, or combination of some of these.

Often the benchmarks for the bond criteria are taken from the repair materials data sheets and relate to laboratory tests.

The expectations to meet these benchmarks at the jobsite, often under difficult real life working conditions, can be unrealistic. Therefore, sound engineering judgment is necessary. The specifications for a specific repair project shall not be blindly copied from other specifications or a *material manufacturer's data sheet, because it may result in situations where it is not physically possible to achieve compliance with the specified criteria.*

A frequently specified test criterion is the bond strength between the repair and the existing concrete substrate. There are numerous examples where the specified bond strength is greater than that of the concrete substrate. Clearly it is pointless to expect the bond value to be greater (or even equal) than the tensile strength of the substrate concrete.

Thus more consideration needs to be given in specific project specifications to the requirements of the project. The test criteria shall consider the results of the existing condition evaluation carried out.

The key requirement of a successful repair is an adequate bond between the repair and existing substrate, <u>which remains intact throughout its service life</u>. At the present time, practical answers to the problems of bond may depend only on short term bond testing rather than on long term performance. An initially achieved specified bond strength is only an indication of performance with the specified parameters. There is no well-defined relationship between initial bond strength and the lasting interfacial bond in a repair system.

Longevity of the bond is influenced by many factors including substrate surface preparation and texture, relative volume changes of repair material, mass transport, service conditions, and quality of the underlying concrete.

3.5.6 Bonding Agents

Bonding agents are not recommended for repairs and overlays employing cement-based materials. Their use cannot compensate for inadequate surface preparation and may act as bond breakers when used inappropriately.

Commentary

Bonding agents should typically only be used if the manufacturer of a proprietary concrete repair material recommends its use.

In some cases, the quality of the concrete surface preparation for repair is being neglected due to a false assumption that poor preparation can be compensated by using a bonding agent. In other cases bonding agents are being specified and used as a "belt and suspenders" measure.

Bonding agents provide an additional step and a material layer that can cause failure, e.g. a bonding agent that is allowed to cure prior to *material placement, becoming a bond breaker. Also, a bonding grout may have a high water-cement ratio leading to a low strength and risk of adhesive failure within the bonding agent layer itself.*

In general, the use of bonding agents should be avoided whenever possible since it leads to two interfaces and thus to the creation of two possible planes of weakness instead of one.

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[1] Bissonnette, Benoît, Alexander M. Vaysburd, and Kurt F. von Fay, "Best Practices for Preparing Concrete Surfaces Prior to Repairs and Overlays," Report No. MERL 11-XX, Bureau of Reclamation, December 2011.

[2] American Concrete Institute, "Concrete Repair Guide," ACI 546R-04, Farmington Hills, MI.

[3] American Concrete Institute, "Corrosion and Repair of Unbonded Single Strand Tendons," ACI 423.4R-98, Farmington Hills, MI.

[4] International Concrete Repair Institute, "Guide for Selecting and Specifying Concrete Surface Preparation for Sealers, Coatings, and Polymer Overlays," ICRI 310.2-1997, Farmington Hills, MI.

[5] "Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique," ASTM E965, American Society of Testing and Materials, West Conshohocken, PA.

[6] International Concrete Repair Institute, "Guide to Using In-Situ Tensile Pull-Off Tests to Evaluate Bond of Concrete Surface Materials," ICRI 210.3-2004, Farmington Hills, MI.

Appendix B

Development of Performance Criteria for Surface Preparation of Concrete Substrates Prior to Repair and Overlay

Research Proposal

Development of Performance Criteria for Surface Preparation of Concrete Substrates Prior to Repair and Overlay

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The American Concrete Institute Research Council

Development of Performance Criteria for Surface Preparation of Concrete Substrates Prior to Repair and Overlay

Objective and Scope of the Proposed Research

The aim of the concrete repair or overlay is to prolong the useful service life of the deteriorated/distressed structure or its element, to restore the load-carrying capacity and the stiffness, and to strengthen the structure or its member. Consequently, monolithic action in the composite repair structure is the final aim. A prerequisite for monolithic action is sufficient lasting bond between the existing substrate and the new-cast material.

In this respect, of critical importance to the efficiency of the composite repair system is the concrete surface preparation prior to application of the repair material. Proper surface preparation is essential for the durability of the repaired structure. The repair material is often blamed for "not sticking", but the general source of the trouble lies with the substrate surface conditioning.

Regardless of the cost, complexity and quality of repair material and application method employed, the quality of the surface preparation of the substrate prior to repair will often determine whether a repair project is a success or a failure; and whether or not a repaired structure is durable.

The durability, in this context, may be defined as lasting interfacial coexistence of two composite materials combined in a composite system. Although most of the specified requirements and engineers tend to focus on the achievement of the prescribed initial bond strength, it must be noted that although important, this characteristic is not as important and critical as the bond durability as dictated by the service conditions of the repaired structure.

The concrete substrates are different, one from the other, in age, quality and service exposure: from the relatively new concrete to the most deteriorated one, exposed to various temperatures, relative humidity, chemically aggressive interior (inside the concrete substrate) and exterior environments, electrochemical status and mechanical loads.

Our preliminary results allow for the following characterization of the concrete substrate to be repaired/overlayed:

(1) It is physically and chemically very complex

(2) Such complexity is also very variable from case to case

(3) The complexity has to be considered on the basis of scale, which is relevant and dependent on the particular situation

(4) Practical answers and guidance/performance criteria at the present time, as well as the problem of achieving optimum bond in the repair/overlay composite systems, depend more upon broad judgment than detailed knowledge.

A detailed review of literature on bond issues in concrete repair indicates that many critical details and parameters are still little known, and the area needs further research in order to develop standard test techniques for assessing the substrate performance criteria for practical applications.

Therefore, the primary objective of the proposed research is to develop performance criteria for surface preparation of existing concrete prior to repair and overlay. The objective relates to normal weight and also to lightweight concrete surfaces, due to significant differences between them. The research activities will include both laboratory and field testing and evaluation.

The specific objectives of the current project are:

- To evaluate existing in-situ methods for assessment of the integrity of a prepared surface
- To establish correlation between shear bond strength and pull-off tensile strength
- Evaluate effect of load eccentricity in a tensile pull-off test on the bond strength
- To quantify concrete substrate roughness parameters that influence the bond strength and durability
- Develop a field test to evaluate the optimum moisture conditioning of the particular concrete substrate
- Evaluate effect of surface temperature requirements to permit proper wetting by the repair material
- Evaluate effect of carbonated substrate concrete on bond strength and durability

- Develop guide specifications for surface preparation. The specification will address “how to”, and also explain “why to.”

Technical Activities

A number of factors are affecting the influence of the concrete surface on durability of the bond in a composite repair/overlay system: the macro and micro-roughness of the surface, the porosity that will modify the contact angle, absorptivity of the surface, strength of the substrate’s skin, chemical status and heterogeneity, moisture content, temperature, and the hydration dynamics of the cementitious repair material.

The following surface treatment methods will be employed and studied:

- Sand blasting
- Shot blasting
- Water blasting
- Scarification

The following tasks will be performed.

Task 1. To evaluate existing non and semi-destructive methods for in-situ assessment of the integrity of the prepared surface

Obviously, the physical integrity of the prepared for repair surface is of utmost importance in achieving adequate lasting bond. A test program intended to evaluate existing test methods and methodologies directed to evaluation of integrity of prepared surface will be implemented. The quest for a practical test method suitable for field conditions has been investigated in a recent project at Laval University. The method that was developed needs further improvements, but a prototype should be available at the time the program described in this proposal starts. The idea is to come up with a mechanical test able to evaluate superficial cohesion of a concrete surface within minutes, irrespective of its orientation. A statistical analysis of the results will be made in order to assess the overall variability. This will help to establish, for instance, the number of tests necessary to obtain a significant value of superficial cohesion, for a given level of confidence.

Task 2. Establish relationship between tensile bond and shear bond

For concrete repairs and overlays, bond strength presently is defined as ‘the tensile strength perpendicular to the interface plane’. However shear stresses parallel to the interface are equally critical. Consequently, the bond strength in shear is the critical factor in composite repair systems.

Mechanical adhesion in shear differs significantly from the tension. For example, a high interface roughness usually improves the shear bond strength, whereas the tensile bond strength primarily depends on vertical anchorage in pores and voids of the substrate. However, it is much easier to measure the tensile bond strength, and it can be used reliably as a definition of bond if a decent relationship between the two bond parameters is established.

Relating interface bond shear and tension tests is questionable, as both bond mechanisms have substantially different characteristics. Several studies are consistently in agreement that shear bond strength is higher than tensile bond. However; there is a lot of contradiction in the magnitude of the correlation. The measured mean ratio (shear bond divided by tension bond) varies from 1.2 to 2.04 in different studies, which is unsatisfactory for converting the pull-off test results to shear bond strength. The reliable comparison between the shear and the tensile bond strength can be very useful for prediction of the real performance of a repair system in practice.

This task will involve pull-off and shear bond testing of 3-in (75 mm) thick experimental repairs utilizing commercial pull-off and torque testing equipment.

Task 3. Evaluate effect of load eccentricity in a tensile pull-off test on the bond strength.

Load eccentricity in a core pull-off test depends on the normality of the core drilling (relative to the substrate) and accuracy in positioning the metal dolly on top of the core.

In in-situ testing, eccentricity is always a reality; therefore the tensile bond strength measured is not one hundred percent "tensile." The difficulty of putting a bond plane into a uniform tensile stress state due to the eccentricity will be the principal focus of this task.

Task 4. To quantify concrete substrate roughness parameters that influence the bond strength and durability

The surface roughness has been considered to have a major influence on the bond between existing substrate and repair material. Some of the known bond tests, however; have shown that surface roughness has only a minor influence on the bond. In the tests performed by Silfwerbrand (Silfwerbrand, 1990), bond to rough water jetted surface was compared with bond to smooth sandblasted surface. It was concluded that there may be a roughness "threshold value." If the surface roughness is higher than the "threshold value", further improvement of the roughness does not seem to enhance bond strength. According to these tests, this "threshold value" ought to be close to the surface roughness of the typical sandblasted surfaces. However, it is the opinion of many specialists in the industry that rougher surface is beneficial to bond strength. Therefore, further investigations using interface tensile and shear bond tests are to be performed to establish the performance criteria for the substrate surface roughness.

Task 5. Develop a field test to evaluate the optimum moisture conditioning of the particular concrete substrate

The influence of surface moisture on the bond between old concrete and repair is an issue of significant importance.

Moisture condition of the concrete substrate surface at the time of application of repair material has a major influence on the values of absorption of repair mixture's moisture and fines, and therefore on bond strength and durability.

Saturated Surface Dry (SSD) conditioning of the substrate prior to application of cementitious repair materials is usually recommended and used, which underlies the "layman's" instinctive procedures to avoid problems, rather than achieve the most effective bond. Various investigators came to the conclusion that different substrates and repair materials correspond to different optimum interface moisture conditions at the time of casting. The problem is that presently there is no test method to determine the optimum moisture condition for a particular substrate and repair material. A modified capillary suction test is developed at the University of Liege (Courard and Degimbre 2005). The early data on the capillary suction of the prepared surface are very important, especially the speed of water absorption

The objective of this task is to develop an in-situ non-destructive test methods/methodology to evaluate surface and near-surface absorption to recommend the optimum moisture conditioning of the substrate.

Task 6. Evaluate effect of surface temperature requirements to permit proper wetting of the substrate by a repair material

The substrate temperature at the time of surface repair or overlay placing was found to have significant effect on bond strength development and durability. Unfortunately, the effective parameters (surface temperatures versus repair material temperature at the time of placement) are not established. Further testing is necessary to establish performance of substrate and repair material. This will be the objective of this task.

Task 7. Evaluate effect of carbonated substrate concrete on bond strength and durability

Through proper surface preparation the carbonated concrete surface can usually be removed, thereby exposing a "fresh" uncarbonated surface. However, in some cases it involves extensive removal of otherwise sound concrete. Also, long periods of time between surface preparation and repair placement may result in new carbonation of the exposed surface. Test results (Gulyas, Wirthlin and

Champa, 1995) show that carbonation may decrease the bond strength significantly. Block and Porth, (1989) on the contrary, found in their studies that carbonated substrate does not affect pull-off bond strength. Further studies are necessary to resolve the controversy, and they will be performed in this task.

Task 8. Develop performance criteria and guide specifications for concrete surface preparation prior to repair

Based on the results of the research performed and the state-of-the-art established prior to this research project, performance criteria will be developed. The prescriptive type guide specifications will be developed.

Equipment and Human Resources

The proposed research project will be performed in the laboratories and in-situ facilities in North America and Europe. The laboratory work will be performed at Laval University (Civil Engineering Department), University of Liege (Building Materials Research Unit) and the Warsaw University of Technology (Institute of Construction Engineering and Management). The in-situ testing part of the project will be performed at Laval University, US Bureau of Reclamation, Denver, Colorado and Naval Facilities Engineering Service Center, Port Hueneme, California. Research engineers, MSC students and technicians will be involved in the project.

Project Management

Management of the separate research groups will be assumed by the applicants. The overall management and coordination of the project will be performed by B. Bissonnette and A. Vaysburd. The project will be managed using traditional time-line scheduling.

The first phase of the project will encompass developing protocols for the experiments, design and manufacturing of necessary forms and equipment. Tasks 1 and 2 of the project are already underway.

The principal investigators intend to report regularly about the progress of the research to CRC, TRRC and ACI Committees 36A and 546.

In addition, the following groups or agencies will be kept informed throughout the project, notably the consortium CREEP, NSERC *Industrial Chair on Repair and Maintenance of Concrete Infrastructures* at Laval University (*City of Montréal, City of Québec, Degussa Building Systems, Euclid, Hydro Québec, King Packaged Materials, Lafarge, MTQ, St. Lawrence Cement, W.R. Grace & Co*.), the Belgian and Polish Ministries of Public Works, and FEREB (*Federation of Repaired Contractors of Belgium*).

Schedule and Duration

Duration of the project – 3 years.

Year 1 (May 2005 - April 2006)

- Methodology for assessing the integrity of the prepared surface.
- Preparation of precast concrete slabs
- Surface Preparation
- Surface Characterization
- Application of Repair Materials
- Evaluation of eccentricity effects in pull-off tests.
- Correlation between shear bond and tensile bond.

Year 2 (May 2006 - April 2007)

- Completion of the Year 1 activities
- Mechanical profilometry
- Opto-morphometry
- Laser profilometry
- Analysis of results
- Field validation of the laboratory studies and analysis on the substrate surface roughness
- Test and methodology for moisture conditioning

Year 3 (May 2007 - April 2008)

- Completion of Year 2 tasks
- Effect of temperature and carbonation
- Analysis of the research results
- Development of Performance criteria and guide specifications
- Report

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