Point of view

"Realcrete" versus "Labcrete"

Searching for tests that give reliable results

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"Truth lies within a little and certain compass, but error is immense."
—Henry St. John, Viscount Bolingbrok, "Reflections Upon Exile"

As discussed in "Concrete Repair Technology—A Revised Approach Is Needed," published in last month's *CI*, a large number of existing concrete structures worldwide—including previously repaired ones—are presently in a state of deterioration or distress.[1] In that article, the authors "analyzed some common problems with concrete repairs, explored issues that must be investigated further, and attempted to provide revised opinions on various concrete repair issues."

Because concrete repair is a complex process, it presents unique challenges that differ from those associated with new concrete construction. The repair process must successfully integrate new materials with old materials, forming a composite system. The strength and durability of a concrete repair, however, is currently measured the same way as the strength and durability for new concrete structures. Any method capable of rendering concrete repair technology more reliable would have an enormous engineering and economic significance considering the present day volume of deteriorated concrete structures.

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There have been great advances in the understanding of concrete durability, especially in severe environments, yet durability still remains the foremost problem facing the industry today. We only have to look on our newly repaired bridges, parking structures, and buildings to see that we do not yet have adequate solutions; spalling, cracking, rust staining, and corrosion of reinforcing steel are visible problems. But behind these visible manifestations of concrete repair durability problems are more complex, invisible problems. This article will attempt to address some of these invisible problems in detail, namely the problems associated with applying experimental results to field conditions.

A COMPLEX SYSTEM

Cement-based materials are complex. They are a heterogeneous mixture of diverse components, with widely varying characteristics and properties. They are a "soup" consisting of hydrated cementitious materials, aggregates, and admixtures. Many designers do not appreciate the complexity of the concrete repair system; they merely choose a material according to its compressive strength, as measured in the field or some laboratory. Design codes seem to encourage this material selection method, by relating most material performance indicators to the concrete's compressive strength.

Almost all concrete repair design problems are open-ended; they do not have a unique or "correct" solution, though some solutions are clearly better than others. These field problems differ from those used in mechanics and structures classes that generally have single correct answers. The designer needs a better understanding of concrete repair as a unique composite system of materials exposed to a combination of interior and exterior environments. The durability of a concrete repair, however, is not based on the repair material alone—design, detailing, workmanship, and quality control are all important factors. Understanding concrete repair requires an open mind, a willingness to consider all facts, and, of course, knowledge about concrete.

In "new" structures, there is often a well-defined structural system that has been designed and its capacity documented with calculations. In repair and rehabilitation, one has only problems, symptoms, and sometimes causes, often without any information about the structural system. The following are some of these problems:

- What caused the failure or deterioration?;
- What is the remaining service life of the structure (durability capacity)?;
- What is the present load-carrying capacity of the structure?;
- How will the repair treatment affect the overall structure ("side effects")?; and
- Which materials and methods will offer the best (technically and economically) solution?

There is an increased need for designers to pay more attention to "constructibility" issues during the development of specifications and to gain a higher level of knowledge in concrete technology, including field experience. The repair design must contribute to the solution and not be the major problem. Geometry, access, amount and spacing of reinforcement, climatic conditions, available equipment, local engineering and labor skills, quality control, and economical considerations have to be analyzed. Repair specifications are often a mixture of referenced standards and "cut and paste" clauses from previous projects. In the best cases, they tend to be based on borrowed wisdom as opposed to documented performance.

The analysis of premature deterioration of concrete repairs highlights the very essential role played by the construction process in providing the quality needed for a concrete structure to resist its environment. On-site workmanship is a crucial element of the repair success or failure. Poor workmanship results in unacceptable variability in concrete. Variability leads to premature failures due to various destructive processes. All good intentions in a rational design and material selection will fail if not supported by quality workmanship and quality control during construction.

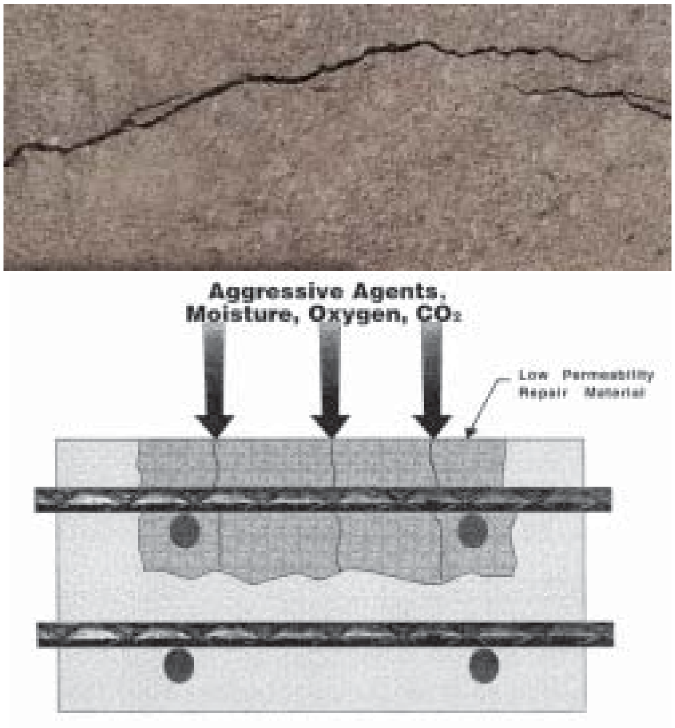

Fig. 1: Cracking in the repair, caused by restrained volume changes, is one of the truly insidious phenomena of repair pathology

RESEARCH AND TESTING

Existing research and testing methods used for evaluating the performance of a concrete repair are clearly unsatisfactory. Many of the laboratory test results are inconsistent. One of the reasons for this is that most of the tests are related to concrete produced and cured in the laboratory—labcrete. This does not allow the researcher or practitioner a complete understanding of the material's in-place behavior and its effects on repaired structures.

Laboratory and experimental testing should study repair-related issues of realcrete—concrete under field conditions. Researchers should consider the environment, repair location in the existing structure, its geometry, restraint, and nonuniformity. Various loading conditions need to be included in such testing programs. To give designers confidence in new technology, research should provide the credible basis on which prognosis of performance and longevity can be made.

For example, cracking in the repair, caused by restrained

Fig. 2: Idealized model of repair failure

volume changes, is one of the truly insidious phenomena of repair pathology (Fig. 1), but permeability testing of materials using laboratory specimens disregards a dominating effect of cracking on permeability. The permeability of cement-based materials (realcrete) has very little to do with laboratory test data (labcrete) or with field permeability tests performed between cracks.

Deterioration and distress of repaired concrete structures in service result from a variety of physical and chemical processes such as the corrosion of embedded reinforcing steel and freezing and thawing. Reinforcement corrosion, however, does not initiate concrete deterioration. Rather, the concrete must first crack. When large, visible cracks become interconnected with microcracks, the network of cracks facilitates the transport of aggressive ions and gases to the embedded reinforcement, leading to premature corrosion and deterioration. Corrosion, more cracking, and concrete spalling are the effects and initial cracking is the cause. Figure 2 shows an idealized model of a repair failure.

Much material science work on durability of concrete is based on short-term laboratory testing in highly artificial conditions. Because it is not possible to simulate the field service conditions by accelerated laboratory tests, these test methods have a limited value for prediction and control of repair durability.

For many years there has been a search for small-scale tests that predict the occurrence and propagation behavior of cracks in engineering structures. The inadequate prediction of cracking sensitivity in full-size repairs is usually associated with unrealistic small specimen behavior in laboratory testing. Laboratory tests are usually inadequate because of one or more of the following basic reasons:

- The small size does not allow the full constraints to be developed, and the critical tensile stress is not achieved;
- General yielding of the small specimen during the cracking process clearly negates the fracture mechanics approach occurring in full-size repairs;
- The strain rate does not reach that associated with a propagating crack in the full-scale repair, where cracks usually propagate at high speeds by absorption of elastic strain energy; and
- It is impossible to model the combined effects of an in-place environment on a small specimen under controlled conditions.

When considering the performance of actual structures (realcrete), the current laboratory tests on durability should be used with caution because the performance behavior of cementitious materials is highly dependent on environmental conditions, specimen geometry, curing history, and, especially, the human factor—workmanship. Laboratory specimens (labcrete) are relatively small, produced by experienced technicians in controlled artificial conditions; usually they are not restrained against volume changes. It is easy for labcrete to yield low permeability values. The same material mixture when used in field structures may not prove to be durable due to the shrinkage cracking, exposure to frequent freezing and thawing, or wetting and drying.

Researchers should concentrate on developing an inexpensive, relatively rapid, reliable method of evaluating repair materials in regard to their future in-place performance. This method would establish a rational yardstick for selecting and specifying repair materials, where strength is of secondary importance.

Part of the reason that we still don't have an answer to the "to be or not to be" question—that is, to protect or not protect reinforcing steel exposed in the repair area by applying an additional protection system—is because of the lack of laboratory investigations of the corrosion performance of different protective systems that correlate to field conditions. Steel reinforcement within a repaired structure usually constitutes an electrically continuous system. For unknown reasons, most of the research and evaluation studies carried out to date have been conducted by exposing the reinforcement to more or less uniform conditions. Thus, the effect of the simultaneous existence of different exposure conditions with respect to various segments of the reinforcement has not been fully understood and has not been evaluated.

To illustrate this point, consider the commonly used method for the evaluation of various reinforcement protection systems in chloride environments by the saltwater ponding test (Fig. 3). The method is being widely used for testing of concrete mixtures, chemical additives, inhibitors, and pozzolanic materials for resistance to chloride ion penetration. This test is useful for evaluating corrosion protection in new construction, if the assumption is made that the concrete is crack-free and the chloride ion transport mechanism is by diffusion.[2] Unfortunately, this method is being unjustifiably referred to and specified for evaluation of corrosion protection of reinforcement in repair systems. This test does not take into consideration the presence of the three phases of a composite system (existing, repair, and transition zones between them), the differences in permeability of existing and repair phases, or the effect of interior environmental variables such as the pH of solutions, presence of aggressive ions, the steel stress condition, and humidity.

No correlation has ever been established between ponding test results and corrosion protection in service. Therefore, it is not surprising that some systems failing the ponding test give good performance in service, and vice versa. It might be argued that at least this test gives some general understanding of the protective capabilities of the tested systems. But when evaluating the complex situation of chloride attack causing corrosion problems in repaired structures, simplifications and generalizations are very dangerous.

When test procedures are planned in relation to well-defined criteria and performance requirements, the results of such tests can be interpreted with greater clarity and can lead to significant conclusions. Often test results have not been planned in accordance with the preceding considerations in mind. Many of the tests reported in the literature have specific and narrow objectives. Interpretation of such tests with respect to their general validity and significance are questionable.

Most likely, some researchers feel that it is up to the designer and contractor to control the conditions in the field and, if this is not done, it is not their concern. Site conditions for realcrete are not perceived to be within the researcher's scope of work.

One realizes that long, slow, expensive field-testing procedures conflict with commercial factors involved. Therefore, a compromise testing program should be devised. Because existing laboratory tests do not satisfy the needs of the industry due to a lack of applicability of the results to real-life situations, site testing becomes a necessity. The advantages of site testing are: the measurements made are specific to the test environment, the level of confidence is high, and the test results can be used to set up reliable accelerated tests.

In the process of selecting repair materials, the first task is to evaluate the material's cracking tendency or extensibility. Extensibility is the material property that prevents restrained cement-based material from cracking, either when it is "stretched" by drying shrinkage or by thermal contraction. In the laboratory, various tests are available to measure free shrinkage. But the internal stress is not predicted (determined) by simply quantifying the free shrinkage properties. Creep and elastic modulus also should be known. Little, if any, information is available, however, on creep characteristics of repair materials. This lack of information makes it nearly impossible to draw direct conclusions and make judgments on the resulting deformations and cracking in concrete repairs. Often materials used based on laboratory data of low shrinkage develop severe cracking, and materials with higher shrinkage do not crack under field conditions.

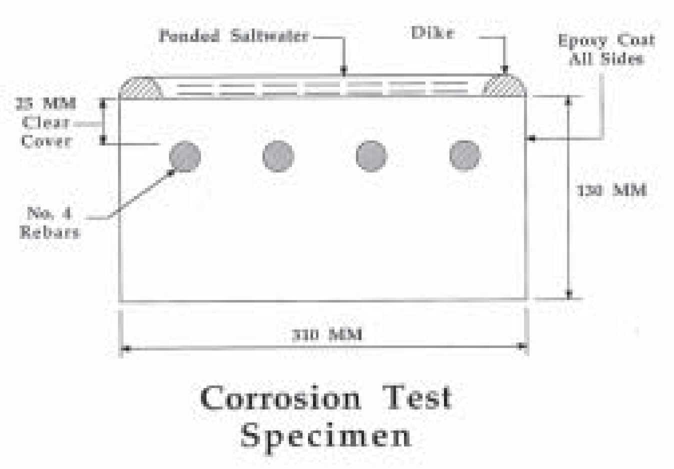

Fig. 3: Schematic of a repaired concrete specimen subjected to a corrosion test

From an analysis of the literature, it is known that prior works on the subject employed modulus of elasticity and creep in compression to analyze cement-based materials' extensibility. These studies were not successful. In our view, the attempt to use the modulus of elasticity and creep in compression instead of in tension was, and is, a major factor making it difficult, if not impossible, to correlate laboratory test data to the actual field performance of repair materials. Knowledge of the tensile properties is necessary in predicting the extensibility of the repair materials and in analyzing the internal stress in the system.[3]

When nearly all material properties of concrete are expressed in terms of its compressive strength, engineers are encouraged to disregard the complexity of cement-based materials. It is well known that the translation of tensile into compressive properties is rather problematic (if not arbitrary), especially for repair materials. In this respect, it is first interesting to recall briefly that the fracture behavior of a cement-based material in tension is markedly different from its compressive behavior. From fracture mechanics it is known that cracking in a tensile stress field is unstable and that the driving force that extends the crack is directly related to the crack length. In compression, however, the driving force is independent of crack length, and the formation of cracks does not constitute an unstable condition.

Also, at least during the early ages, the creep under tensile stress is greater than that under compressive stress. At later ages, the rate of creep is less under tensile than under compressive stress. In concrete repairs, the tensile properties of cement based materials—not compressive properties—greatly influence the cracking mechanism, the bond and shear behavior, and the failure criteria under the stress. If this statement is true, why are we still witnessing the status quo in this regard? Simply, because compressive tests are much easier to perform than direct tensile strength, tensile modulus, and creep tests.

Let's be honest with ourselves. We know about 60% of the answers to questions we should know to really do the repairs properly. Nobody can wait until we get the other 40% of the answers, so we have to do the best today. We must make performance tests reliable. The tests will give us the right answers if we ask the right questions. According to Leonardo Da Vinci, "Experiments do not ever err, it is only your judgment that errs in promising results which are not caused by your experiments."

It is hoped that the few thoughts highlighted in this article will help to form the basis for a better understanding of concepts in concrete repair by enlightened designers, specifiers, material manufacturers, and contractors so that many of the misconceptions that prevail presently can be avoided and the pointers here act as a guide for more meaningful and successful repair projects.

To finish on a positive note: We do not think that we have beaten this subject to death by any means. We hope we have beaten some more life into it.

FINAL POINTS

1. The industry urgently needs to test (evaluate) cementitious repair materials in such reproducible ways so that practitioners are confident when specifying and using them. If this goal is reached, we will be better able to make intelligent adjustments when deviations in performance are experienced.
2. If the repaired structure is to be durable, along with other controlling factors, appropriate measures must be taken to control volume changes and the resulting induced cracking of the cementitious composites used for repair. Testing of related fundamental properties that control the durability of concrete have to be perfected to allow for reliable prediction of performance in the environment of service.

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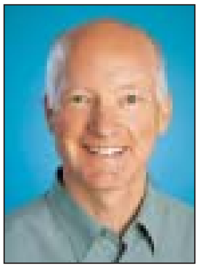

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