Structural concrete repair – A durability based revised approach is needed

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"Just as walking is but a succession of interrupted falls, the entire history of human progress is a succession of stumbling half-truths and misinterpreted facts. The 'accepted facts' of today become the 'recognized fallacies' of tomorrow."

– ACI Past President Herbert J. Gilkey (1950)

In recent years, durability problems, poor performance, and, most of all, repair failures have tarnished the public's image of concrete. Repair failures and endless "repair of repairs" make a substantial contribution to the current perception of concrete. Concrete often gets a bad name because premature repair failure is one of the most visible manifestations of poor design decisions and details, and inadequate field practice.

Concerned with the current state of concrete repair technology, the author wrote this article in an attempt to improve the performance of repaired structures. To do so, the author has analysed some common problems with structural repairs especially those in coastal regions, explored issues that must be investigated further and attempted to provide revised opinions on various concrete repair issues.

Introduction

Various factors have impeded improvements in the durability of concrete repairs, including: inadequate condition evaluation and design; lack of quality construction practices and quality control; and the choice of repair materials (that may be incompatible with the existing substrate). It is necessary to reconsider some recent developments in structural repairs from the view point of extending the service lives of structures under repairs.

Because the subject of this article is devoted to "what is wrong?" and "what the confusing issues are", one should first discuss several key issues in an attempt to establish the facts. This paper covers a broad field, hopefully in a thought provoking manner. One should fully realize, however, that an attempt to deliver comprehensive analysis and offer solutions to concrete repair problems in one article is too ambitious and quite an impossible task. Let's share, however, Aristotle's view that "a plausible impossibility is always preferable to an unconvincing possibility".

'Confused state of the affairs' – A complex problem

Concrete deterioration is a complex problem that requires the designer to understand concrete's microstructure (for diffusion of chemical species) and its macrostructure (for permeation through cracks and damage). The heterogeneity of the components in a composite repaired structure requires an understanding of the interaction of the existing materials and the repair materials. In addition, it is also important to understand that the durability of the repair is a function not only of its basic components, but also as to how such components (and the system as a whole) respond to the exposure conditions of the structure. The durability of a repaired concrete structure depends on its ability to resist a variety of chemical and physical agents that attack all parts of the composite structure with different degrees of intensity, externally and internally.

There is a need for increased knowledge in many of the research studies, design practices, and construction practices in the concrete repair field. Too often, product developers do not pay sufficient attention to the needs of the marketplace. As a consequence, some materials are often being developed and marketed without there being demands from the field. If the "hit-or-miss" methods often used in concrete repair were applied to new construction, one wonders what would happen to some of our structures.

Analyses of failures of new and repaired structures around the world clearly demonstrate that materials contribute less to the problem, whereas design and in-place workmanship are more influential. The basic principles that affect repair durability are widely known, but very little is being done to improve durability. More often than not, many believe that the simple answer to the repair problems is improving the compressive strength of the concrete or accelerating its strength gain.

Repair materials – What are 'better' materials?

As we have accelerated the pace of concrete construction, we have required cement-based materials to become stronger sooner and to set faster. At the same time, we've increased concrete's brittleness and reduced its resistance to cracking. In this attempt, we have damaged concrete's "immune system." Concrete that continues to hydrate offers increased resistance to aggressive agents. The "old-time" concrete used to gain strength, density, and the ability to resist environmental attack over its service life; "new" concrete does not.

There has been unquestionable progress made in the field of repair materials. But the material that has the required properties for a particular application is only one part of the complex system that makes up a concrete repair.

A repair material has value only when it permits an engineered product—a concrete structure—to fulfil its intended use/purpose, its function.

It means that any considerations of material needs, innovations, and performance must relate to the performance of the final engineering product (Figure 1).

Because repair failures may lead us to believe that the material didn't perform well, the repair solution is often focused on "better materials." But what is a better material? Experience clearly demonstrates that conditions that impair the effectiveness of a repair material in one structure would not necessarily impair the effectiveness of that same material in another structure.

Repairs correct deterioration or distress that affects a structure's serviceability or aesthetics. In major structure rehabilitation, many repairs are on a scale where structural integrity becomes significant and it is necessary to ensure the transfer of load between the concrete substrate and the repair. With such repairs, problems do arise fairly quickly because of the different properties of the repair material and the concrete substrate. Differences between repair materials and existing concrete that affect repair durability include:

- Shrinkage of the repair material relative to the concrete substrate
- Thermal expansion or contraction differences between the repair material and concrete substrate

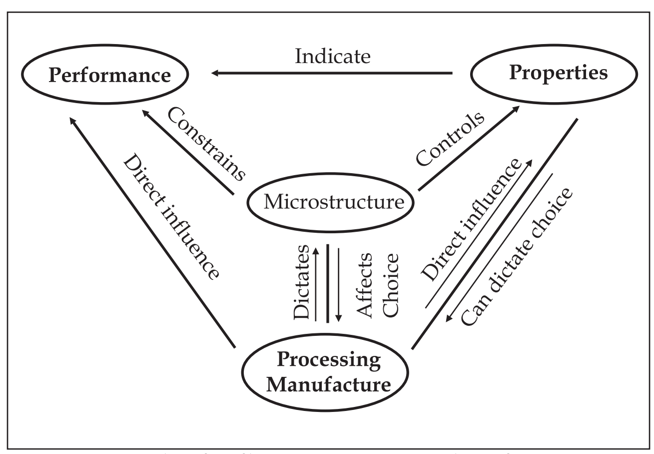

Figure 1. Levels of influcence on material performance

Table 1. General requirements of patch repair materials for structural compatibility

Property	Relationship of Repair mortar (R) to Concrete substrate (C)
Strength in Compression, tension and flexure	R≥ C
Modulus in Compression, tension and flexure	R= C
Poisson's Ratio	Dependent on modulus and type of repair
Coefficient of Thermal expansion	R= C
Adhesion in Tension and Shear	R≥ C
Curing and long term shrinkage	R≤ C
Strain capacity	R≥ C
Creep	Dependent on whether creep causes desirable or undesirable effects
Fatigue performance	R≥ C
Chemical reactivity	Should not promote alkali-aggregate reaction, sulphate attack or corrosion of reinforcement in the substrate.
Electrothermal stability	Dependent on permeability of patch material and chloride ion content of substrate.

- Differences in stiffness and Poisson's ratio causing unequal load sharing and strains resulting in interface stresses
- Differences in creep properties of repair material and the concrete being repaired; and
- Relative fatigue performance of the components in the composite repaired structure.

Such differences do result in initial tensile strains that either crack the repair material or cause debonding at the repair-substrate interface. Both of these results normally reduce the load-carrying capacity and durability of the structure. Therefore, selecting the appropriate material for the repair is imperative. Table 1 lists the properties generally required of repair materials when compared with the concrete substrate to produce long-term structurally efficient repairs.[1]

The lack of widely agreed upon methods of testing leaves repair materials subject to a limited evaluation that is driven more by manufacturers than by users. All too frequently only the isolated properties of repair materials are emphasized, whereas the more important properties of the composite are neglected. The author feels that testing of the composite repair under simulated field conditions is more appropriate.

Design and field practice

The concrete industry could learn a lot from concrete repair failures had adequate information been available. Unfortunately, it seems that only catastrophic structural failures (resulting from inferior design and poor quality materials and workmanship) are publicized. Information about other repair failures, although they may be serious and extremely costly, is generally not available. A better understanding of the initial factors and properties affecting the performance of repaired structures is critical to the longevity of a repair. Because data on causes of concrete repair failures do not exist, let us take a look at the results of various analyses of damage in concrete construction.[2] The British Cement Association reviewed factors that contributed to the failure of structures. They found the following attributes corresponded to the respective percent of failures:[3]

- 11.6%, low cover
- 38.5%, environment
- 15.8%, poor quality concrete
- 7.2%, poor quality detailing
- 4.2%, poor workmanship
- 1.5%, wrong specification
- 7.7%, failure of joint/waterproofing
- 0.5%, inadequate conceptual design and
- 13%, wrong material selection.

The ACI survey of faults in concrete construction revealed[9,6]

- 57% of defects occurred in design and
- 50% of defects occurred in construction.

The total of 107% is due to the multiple errors associated with the same failures.

Literature shows that 99% of quality-related defects were due to poor design, detailing, specifications, workmanship, and management.[4,2] Other factors, including materials, account for the remaining 1%. At the global level, one can conclude that even with substantial advances in the field of repair materials, the industry will still have an unacceptable high level of defects and failures.

It is generally observed "In this era when there is a great push in our industry for improved construction materials and practices, it will do us no good to have technology that provides 'high-performance concrete' (buzzwords of the early 1990s) if we don't have 'high-performance people' to implement this technology."[5] A lack of attention to detail in design, poor in-place workmanship, and inadequate quality control cause the majority of faults and problems in the concrete repair field (as well as in new construction). Adequate attention needs to be given during the condition evaluation phase of the project, but it is often ignored. Repairing concrete is somewhat analogous to the treatment of disease. Before remedies can be correctly prescribed, the illness has to be diagnosed, and before the accurate diagnosis is possible, the doctor has to have a thorough knowledge of the disease and its various symptoms treatments and history.

The concrete "doctor" needs similar knowledge to prescribe successful treatments for troubled structures. It may be shocking to observe a professional structural engineer who has a limited knowledge of cement-based materials. It must be clear to an engineer that overstress is always the cause of cracking produced in materials, regardless of what factors induced the stress in excess of the material's strength.

It also must be recognised and understood that a repair is not a '*Band-Aid*®' that simply covers a concrete structure problem. This incorrect view lends credence to the prevailing viewpoint that concrete repair is so simple that anyone can do it. Most India and most U.S. construction can be characterized as "low-bid, hard-dollar contracting," and, as an *Engineering News-Record* editorial of December 1, 1988, stated, "Clients that want cheap will get cheap."[6]

The cost to design and construct repairs for durability is minimal when compared with the cost of repairing a prematurely deteriorated, already-repaired structure. When addressing problems with repair technology one must also mention the habitual use of outmoded specifications for concrete repair. How good should the repair material be to serve the intended purpose? Supposedly, the most cogent answers should be found in the specifications for a particular project. But, how many specifications list a drying shrinkage limit instead of a slump and 55 MPa (8000 psi) compressive strength?

Design details and specifications are usually a mixture of referenced standards and "cut and paste" clauses from previous projects. The old adage "a little knowledge is dangerous" is often evidenced by the engineer's specifications and his or her on-site direction. Adding to poor workmanship are the specifications, which are in legal language and make frequent reference to the "direction" of the so called engineer-in-charge. This uncertainty makes sound bidding nearly impossible and may later place the contractor in an unfair unilateral situation. It is also very troubling the way we often do things with regard to concrete repair, sometimes making very questionable assumptions (for simplicity) and then applying high precision requirements. The engineer is also under economic pressure. This pressure may deter engineers from presenting the client with a sound remedial solution based on sound judgment. The engineer has an obligation to the profession and to the client to offer the most promising design solution within the reasonable limits of the economy. The choice of the best alternative must be the engineer's alone, and the responsibility of the efficiency of the work is also the engineer's alone.

Construction practices and workmanship bring us to the problems associated with the people who actually make and repair concrete. Artisans and supervisors are truly the backbone of the concrete repair industry, and unless they are skilled, a great part of the time and money spent in condition evaluation, design, and materials manufacturing is wasted. There is an urgent need for technical training and skills improvement of field personnel. The use of adequate design and "good" materials is of critical importance, but they are not enough without proper execution.

Research—problems and opportunities

Research has substantially improved our knowledge of cementitious materials, the fundamentals of concrete deterioration from carbonation-induced corrosion, chloride-induced corrosion, sulphate attack, alkali-aggregate reaction, and frost. Several research studies in the repair field have been concerned with the improvement of properties of repair materials and their dimensional behaviour relative to the existing substrate. But these activities will lead to improvements in repair durability only if the issues of electrochemical compatibility are also addressed. Removing deteriorated concrete (see Figure 2) and replacing it with a repair material, even with the best one, may result in accelerated reinforcing steel corrosion due to macrocell formation.

In view of the serious and insidious nature of the corrosion of steel in concrete repair and repair failures,

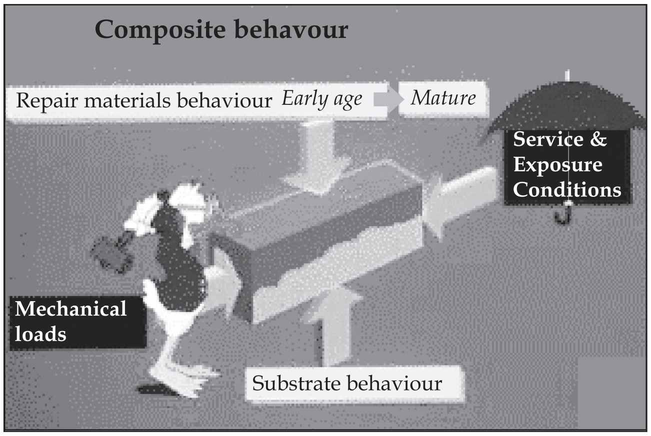

Figure 2. Materials exposed to exterior and interior environments and their interaction

it is surprising that progress in this area has been so slow.

The fact that the progress has been slow is probably attributable to some combination of the following:

1. Concrete repairs are a complex system of materials exposed to exterior and interior environments and its interaction
2. Fundamental guidance for addressing corrosion problems does not exist. The mechanism of passivation and corrosion of steel is poorly understood in complex repair environments. At this time, the whole area concerning "additional protection" of reinforcement in repair is subject to numerous speculations
3. Corrosion of steel embedded in cement-based materials is a complex phenomenon involving environmental, metallurgical, interfacial, and continuum considerations. Most of the research in this area is being done by the civil engineering departments of universities where few workers have knowledge outside their respective specialities
4. Industry and government agencies have limited their support of research that could lead to a resolution of the problem
5. Most hope that repair problems can be resolved by using "high-performance" materials, corrosion inhibitors, protective coating, or "belt and suspender" systems; and
6. Significant knowledge to design durable repairs already exists in a relatively "quite refined state," as Mather stated.[7] But the manner in which this knowledge is used is primitive.

Many areas need further studies, but the priorities must be given to:

- Relating testing to construction practices;
- Resolving the complex issue of electrochemical incompatibility—risk of premature corrosion in repaired structures; and
- Educating in the field of concrete durability and repair.

The ability to define the macro-environmental changes in a composite system caused by a repair is still needed.

This ought to be a major challenge to applied research. The foggy issue of the response of the repaired structure to the changes exerted by the repair must be understood. There is an urgent need to know how to properly assess the nature and severity of the interior environment in the repair system, the possible changes inside the system, and the possible interaction of the repair with the exterior environment to get a reliable estimate of the service life of the repaired structure or the time to the next remedial action. One should then, from the analysis of environmental influences and repair system constitution, use guidance and criteria by which to select materials, protective systems, and repair methods that will, with a reasonable probability of success, and in compliance with the budgetary limits for their project, give a repaired structure that will not prematurely fail. In extreme conditions, following the basics may be insufficient to achieve the intended service life without additional protective measures. These measures can be taken in addition, but not as substitutes, for getting the basics right.

To create confidence in the technology, science should provide a basis on which prognoses of performance and longevity can be made. We have to be able to evaluate the repair materials in such a reproducible way as to be confident when specifying and using them. At the same time, our scientific understanding should broaden so that practical exploitation is soundly based.

If this task is reached, we will be better able to make intelligent adjustments when deviations in performance are experienced.

Suggested initiatives

As discussed earlier, a lack of attention to condition evaluation, design objectives and details, and poor construction practices cause the majority of faults and problems in concrete repair field.[8,9,10] Unless the designer and the artisan are skilled at their jobs, the great part of the money spent in developing improved performance materials is wasted.

Therefore, it is necessary to approach the improvement in rehabilitation/repair performance in two stages. Stage 1 must address the most serious problem at hand reduction of design and worker errors. The success in this stage can only be achieved by improved education and training of all involved in the concrete rehabilitation/repair process. ACI, ICJ, IBC, ICI, universities, and others must take the leadership position in achieving this.

Stage 2 then will address the introduction of improved performance materials for the intended use. The success of this stage will be possible only when Stage 1 is complete and the incidence of errors is greatly minimized. The attempt to introduce Stage 2 before or simultaneously with Stage 1 will simply divert attention from more critical issues and will most likely hold back (rather than help) the achievement of the desirable repair durability.

A reasonable route forward, therefore, seems to be to look for radical changes in education, design, and construction practices, and for incremental improvements in materials.

In achieving cost-effective durable concrete repair projects, we must combine a fundamental understanding of the deformability of materials and the deterioration processes, derived from short-term laboratory studies, with long-term data from field structures including good and bad performances. We will need to develop standards, change design practices, material specifications, contract procedures, and site practices. Our success in the repair field may depend on our ability to resolve the controversies, to differentiate sense from nonsense.

To finish on a positive note—the author is convinced that the trend in concrete repair field has been slow but always forward moving. There are promising activities at work to change the progress in this field from "pedestrian" to "high speed." There is hope that these combined activities may be a springboard for substantial progress.

And if we are in agreement that the future is controlled by the amount of work yet undone, then the future of concrete repair is assured.

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