REPAIR, RENOVATION AND STRENGTHENING OF CONCRETE STRUCTURES

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The extent of deterioration to concrete structures globally is occurring at an alarming rate, which challenges engineers on this continent and throughout the world on a daily basis. This includes damage to bridges, buildings, parking structures, environmental facilities, as well as other structures. Unfortunately, repair costs can be staggering. Delaying repairs usually results in much more costly repairs later. Furthermore, if concrete deterioration or damage is not addressed, some of these structures eventually may cease to be serviceable and worse yet, failures could occur.

There are a multitude of methods and materials available to repair concrete. Additionally, there is an abundance of references which deal with this problem. The International Committee of Concrete Repair (ICRI) and some committees within the American Concrete Institute (ACI) as well as other organizations throughout the world are devoted to developing methods for repair and to disseminate information to professionals regarding the repair of concrete.

Two excellent resources that cover this topic in great depth are:

1. ACI 546R-96, _Concrete Repair Guide_
2. _Concrete Repair Manual_, published jointly by ICRI and the ACI. This is a compilation of various repair documents currently available in North America, and will soon be expanded to include documents from Europe.

Concrete repair, strengthening and renovation is an immense subject. The intent of this paper is to present an overview of the topic. This will include a discussion of how to approach a concrete repair program, as well as introducing some of the commonly used repair techniques and materials.

Typical Concrete Problems:

- Poor Quality Concrete
- Corrosion-related deterioration
- Carbonation
- Freeze-thaw damage
- Earthquake damage
- Design-related
- Substandard workmanship
- Environmentally-related
- "Halo of Anodic" Ring effect

Poor quality concrete: The quality of concrete in a structure will impact the long-term performance. Good durable properly-consolidated concrete, placed with the minimum of honeycombing and internal shrinkage, will provide an environment that should protect the embedded reinforcing for years before repairs are required, if ever.

Corrosion-related deterioration: Corrosion of embedded reinforcing steel is the most common cause of concrete deterioration. When the iron in steel is exposed to water, oxygen, and chlorides, it oxidizes and produces corrosion (rust). The oxidized metal can expand up to 10 times its original volume, resulting in intense bursting forces in the surrounding concrete. This will eventually lead to cracking and delamination.

Carbonation: In normal concrete, the reinforcing is protected by the naturally high alkalinity of the concrete with a pH of about 12. A passivating layer of stable mineral scale is formed on the reinforcing which protects it from corrosion. Carbonation is the reduction of the protective alkalinity of the concrete. It is caused by the absorption of carbon dioxide and moisture which lowers the pH to 10 or less and renders the reinforcing vulnerable to corrosion. Reinforcing steel embedded in carbonated concrete will corrode in the presence of water and oxygen.

Freeze-thaw damage: Freeze-thaw damage is more likely to occur in poor quality concrete, especially if it is not air-entrained. This is a problem in the colder climates with a wide variation of temperature on a daily basis.

Earthquake damage: This is a problem here in Mexico City as well as at various other locations throughout the world. There are methods to modify and/or strengthen existing structures to meet current earthquake standards. Earthquake issues are not addressed by ACI 546 but are instead the responsibility of ACI Committees 341 and 369.

Design-related problems: Improper design or detailing can occasionally result in damage or deterioration to that structure. The lack of proper expansion joints in large concrete tanks, for example, will often result in significant cracking.

Substandard workmanship: Misplaced reinforcing, for example, is a common problem in concrete structures. This often results in severe cracking, and eventually leads to delamination because of corrosion.

Environmentally-related problems: Structures located along seacoasts, or in northern climates where deicing salts are used, for example, often have serious problems with corrosion of the underlying reinforcing steel because of its contact with chlorides.

"Halo of Anodic" Ring effect: It is common for the same reinforcing bars to extend from a repaired area to an adjacent un-repaired, contaminated concrete. Because the same bar extends into two distinctly different environments, conditions result in an electrochemical process, which fosters corrosion where the new repair and parent concrete meet (bond line). The build-up of rust at the surface of the reinforcing, usually in the original concrete, results in spalling, typically around the perimeter of repair patches.

Repair Methodology:

There must be a basic understanding of the underlying causes for the concrete deficiencies prior to selecting repair techniques or materials. Quite often it is not possible to eliminate the reasons that caused the deterioration. An example of this is inadequate concrete cover over reinforcing bars on the façade of a building. The best option is to use repair techniques which take into account the inadequate cover and to provide an appropriate protection system.

Concrete Repair Program:

The basic steps for a repair program include:

- Current condition evaluation
- Selection of repair methods and repair materials
- Preparation of Repair Documents
- Bidding/Negotiation process
- Execution of work

1. **Current condition evaluation:**

   The objective of the condition evaluation is to find the cause for the deterioration or distress and to determine the extent of corrective work that is required. The tasks for a condition evaluation ideally/should include:

   - Review of all available drawings, reports, maintenance records or any other pertinent documents.
   - Perform structural analysis for the deteriorated condition if warranted, to determine if there are any safety issues.
   - Visually inspect the entire structure. As much of it as possible should be sounded to determine the extent of deterioration. Record all results.
   - Implement appropriate testing program. The purpose of the testing program is to evaluate the extent of corrosion activity, the properties of the concrete and reinforcing, the condition of concrete and to collect any other data that might be useful to determine the cause for the deterioration and to help establish an appropriate repair program.
   - Carefully evaluate all laboratory results and other findings from the testing program.
   - Analyze findings to determine the cause for the distress.
   - Prepare an evaluation report including findings, conclusions, and recommended repair program along with an opinion of cost to implement the repairs.

   The concrete testing program should be designed to yield the necessary information to properly assess the structure. The testing program may include:

   - Determination of the locations of delamination by sounding with a hammer or chain drag or any other device. Note that good concrete, when tapped, has a pinging sound whereas delaminated has a dull sound.
   - Determination of chloride levels of the concrete. Reinforcing steel in concrete with high chloride levels is more likely to corrode.

- Determination of corrosion activity within the concrete. This is accomplished by such methods as copper-copper sulfate half cell.
- Taking cores from existing concrete to perform compression tests to determine its strength. This can be supplemented by Windsor Probe or non-destructive tests, such as a Swiss Hammer.
- Determination of internal tensile strength of concrete or at bond line of repairs by performing bond or pull-out tests.
- Determination of physical properties of concrete, such as internal cracking, freeze-thaw damage, estimate of air void system and other pertinent data, with a Petrographic Analysis (microscopic evaluation).
- Determination of levels of carbonation.
- Testing to determine if there is any internal cracking or voids with impact-echo tests.
- Testing with radar to locate reinforcing steel.
- Testing with pachometer to locate reinforcing steel.

2. Repair Materials and Methods:

A. Considerations prior to implementing repair program

Sometimes it makes more sense to repair the ongoing problems than to eliminate the cause. This might be the case for a parking garage scheduled to be replaced in a few years. Spot repairs would be appropriate, as opposed to a more aggressive repair program. The objective would be to keep the structure safe and operational.

When selecting repair methods and materials, outside constraints must be considered such as:

- Limited access to work areas
- Operating schedule (when owner will allow work to take place)
- Budget limitations
- Required useful life of structure (The repair program should be consistent with objective of owner. For example, the minimum repairs should be done if the structure is to be demolished in a few years.)
- Weather implications

There may be constraints imposed by governmental agencies which have to be considered. This could include regulations regarding:

- Airborne vapor and/or particles
- Noise
- Hazardous waste
- Other governmental restrictions

Structural safety issues must be considered prior to implementing repairs, as well as throughout the duration of the repair program. If, for example, during an initial evaluation there is a concern regarding the structural integrity of a parking deck, it would be prudent to provide temporary shoring immediately.

B. Repair Materials

Before selecting repair materials, consult with manufacturers to get a sense of what materials are available, the methods of installation, cost effectiveness and technical feasibility to use certain products. Be aware that manufacturers or vendors may not inform you of the limitation of their materials. It is important that the specifier carefully researches the repair materials that might be appropriate for the project before making a final selection.

When selecting repair materials, a primary objective is to match the properties of the repair material as closely as possible with the parent concrete. In particular, the strength, the modulus of elasticity and the coefficient of thermal expansion should be as close as possible to the parent concrete. In addition, shrinkage of the material is a very important factor, especially when the repair patches are constrained.

There are two basic categories of materials—cementitious and polymer.

1) Cementitious

- Conventional concrete -- will be easy to match the properties of the original concrete
- Conventional mortar
- Dry pack -- a cementitious material with a low water-cement ratio that exhibits very little shrinkage which can be used for filling large or small cavities.
- Ferrocement -- commonly constructed of hydraulic cement mortar reinforced with closely spaced layers of continuous and relatively small diameter wire mesh (not widely used).
- Fiber-reinforced concrete -- conventional concrete with either metallic or polymeric fibers added to achieve greater resistance to plastic shrinkage.
- Grouts -- cement grouts are mixtures of hydraulic cement, fine aggregate and admixtures. Chemical grouts consist of solutions of chemicals that react to form either a gel or solid precipitate.
- Low slump dense concrete
- Magnesium phosphate concrete and mortars -- very rapid strength development and heat are produced.
- Preplaced-aggregate concrete -- drying shrinkage is about one-half that of conventional concrete.
- Rapid-setting cements -- such as Type III Portland cement with accelerators for full-depth sections.
- Shotcrete -- a mixture of Portland cement, sand, and water “shot” into place by compressed air.
- Silica-fume concrete -- silica fume (a by-product of the manufacture of silicon and ferrosilicon alloys) when added to concrete will increase compression strength and decrease permeability.

2) Polymer
   - Polymer-impregnated concrete (PIC) -- a hydrated Portland-cement that has been impregnated with a monomer that is subsequently polymerized. This material is not used very often.
   - Polymer-modified concrete -- Portland cement and aggregate combined at the time of mixing with organic polymers that are dispersed or redispersed in water.
   - Polymer concrete -- composite material in which the aggregate is bound together in a dense matrix with a polymer binder.

The following factors should be considered when selecting a repair material:

- Coefficient of thermal expansion
- Shrinkage
- Permeability
- Modulus of elasticity
- Chemical properties (pH close to12 is desirable)
- Electrical properties
- Color and texture properties

The following references are now available regarding repair materials:

- ICRI Guideline No. 03733 *Guide for Selecting and Specifying Materials for Repair of Concrete Surfaces*.
- ACI 546R-96 *Concrete Repair Guide*, Chapter 3.

C. Concrete Protection

Concrete protection systems may be incorporated into a repair program to extend the life of repairs and minimize future deterioration. In some cases, they will improve the appearance of the repaired structures.

1) Surface applied Protection systems include:
   - Penetrating sealers -- materials which, after application, are generally within the substrate of the concrete. Such products include boiled linseed oil, silanes, siloxanes and high molecular weight methacrylates.
   - Surface sealers -- products of 10 mils (0.25 mm) or less in thickness that generally lay on the surface of the concrete. Such products include varieties of epoxies, polyurethanes, methyl methacrylates, moisture-cured urethanes and acrylic resins.
   - High-build coatings -- materials with a dry thickness greater than 10 mils (0.25 mm) and less than 30 mils (0.75 mm) applied to the surface of the concrete. Such products include acrylics, styrene-butadienes, polyvinyl acetates, chlorinated rubbers, urethanes, polyesters, and epoxies.
   - Membranes -- systems with a thickness of greater than 30 mils (0.7mm) and less than 250 mils (6 mm). Such products include urethanes, acrylics, epoxies, neoprenes, cement, polymer concrete, and asphaltic products.

- Overlays -- products over 250 mils (6 mm) in thickness that are, in general, bonded to the surface of the concrete. Such products include concrete, polymer concrete, and polymer-modified concrete.

The selection factors when comparing the various systems and products include:

- Track record
- Cost
- Appearance
- VOC (volatile organic compounds) compliance with governmental regulatory agencies
- Compatibility with substrate
- Durability and performance

2) Cathodic Protection

The corrosion process is an electrochemical process where anodic and cathodic areas are formed on the steel. When the anodic and cathodic areas are electrically continuous and in the same electrolyte, corrosion at the anodic areas will occur. The corrosion is created as an electrical current flow occurs through the corrosion cell, anodes cathode and electrolyte. For reinforcing bars embedded in concrete, unless mitigated, the corrosion will continue, ultimately resulting in cracking, delamination and spalling of the concrete adjacent to the reinforcing. (From ACI 546R-96, Section 4.3).

An effective method to control the corrosion of steel in contaminated concrete is cathodic protection. The basic principal is to make the embedded reinforcing steel cathodic, thereby preventing further corrosion of steel. This can be accomplished by electrically connecting the reinforcing steel to another metal that becomes the anode, with or without the application of an external power supply.

Cathodic protection systems without an external power source are referred to as sacrificial systems. The metal used to protect the steel is “less noble” or more prone to corrosion than the steel. Zinc is commonly used for this purpose.

Cathodic protection systems using an external power source are referred to as impressed current system. This method incorporates an external power supply to force a small amount of external current through the reinforcing steel. The purpose of this current is to counteract the flow of current caused by the corrosion process. A metal that corrodes at a very slow rate, such as platinum, is typically provided to serve as an anode.

D. Surface Preparation

Probably the most important task to achieve successful concrete repairs is the surface preparation. Good surface preparation requires that minimal damage be done to the remaining concrete at the bond line. Any loose concrete as a result of micro-cracking must be removed. This can be achieved by abrasive blasting or high pressure water jetting. The surface also needs to be clean, free of contaminants, and roughened to an appropriate amplitude for the selected material.

The edges of concrete patches should have shoulders to avoid feathering. This is usually accomplished by saw cutting. Repair patches should be made as regular as possible and re-entrant corners should be avoided. See attached Drawing RS1-1 reproduced from ICRI Surface Preparation Guideline 03730.

It is difficult to determine the extent of concrete removal until the work is implemented. The actual quantity of required concrete repairs may vary from the work as shown and specified in the repair documents. Initially the extent of the area to be repaired is sounded with a hammer, chain, or other device to determine the approximate area of removal. All delaminated, unsound, or otherwise unsuitable concrete must be removed.

The concrete removal must extend around the existing reinforcing with approximately ¾ Inch (19mm) clearance. At mats of reinforcing, if the lower layer is not corroded and tight, the removal need not extend below the lower layer. If the lower layer of reinforcing is also corroded, the removal must extend below the lower layer. Refer to Drawings RS1-1, RS1-2A and RS1-2B, which are based on ICRI Surface Preparation Guideline 03730.

Impact methods for concrete removal, such as jackhammers, can result in micro-cracking of the substrate. The lightest hammers possible should be used to minimize this impact. Care must be taken to remove all loose concrete prior to installing any overlays or repair materials.

For larger projects, hydrodemolition might be an option. This method removes concrete with high pressure water jets which is efficient and leaves a rough profile. After the surface is thoroughly cleaned, it usually is very satisfactory for bonding new concrete. Although, micro-cracking is minimized, containment and subsequent disposal of the water can be a problem.

Note: A typical “Concrete Repair Procedure” is attached to this paper as an example of the steps required to attain proper concrete repairs. It is intended to be used only as a guide and must be modified appropriately for each project. The author cannot assume any liability for its use on any project and does not warrant its accuracy.

References for methods of removal and preparation include:

- ACI 546R-96, *Concrete Repair Guide*, Chapter 2
- ICRI Guideline No. 03730, *Guide for Surface Preparation for the Repair of Deteriorated Concrete Resulting from Reinforcing Steel Corrosion*

E. Repair Methods

The method of repair should be designed and detailed to mitigate the damage or deterioration as much as possible. Sometimes it is necessary to rebuild portions of the structure as part of the repair program. There are times when strengthening is required, in addition to repairs. Each project must be carefully evaluated, as previously discussed, prior to selecting a repair method appropriate for that job.

Deterioration adjacent to concrete repair patches commonly occur because of the "Halo of Anodic" Ring effect. When the same bar extends into two distinctly different environments, conditions result in an electrochemical process which may result in corrosion where the new and parent concrete meet (bond line). The build-up of rust at the surface of the reinforcing, usually in the original concrete, leads to spalling, typically around the perimeter of repair patches. This problem must be addressed in repair programs to delay the onset of future corrosion and the need for repairs. The methods to mitigate this problem include:

- Protective coatings
- Migrating corrosion inhibitors
- Cathodic Protection-impressed current
- Cathodic Protection-passive systems

The most common repair methods include:

1) Cast-in-place concrete — Repair by conventional concrete is generally the replacement of defective concrete with new concrete.
2) Form and pour — Formed and poured concrete is a method of replacing damaged or deteriorated concrete by placing a repair mortar in a formed cavity.
3) Troweling — This method is used for shallow and/or limited areas of repair. These repairs are generally made with Portland cement mortars, proprietary cementitious materials or polymer-modified grouts or polymer grouts and mortars.
4) Dry packing — Dry packing is the hand placement of a very dry Portland cement mortar, which is tamped or rammed into place.
5) Preplaced aggregate — In this method the aggregate is placed in the forms first and the voids are filled by pumping in a cementitious or resinous grout. A benefit of this method is a significant reduction of dry shrinkage.
6) Shotcrete — This method involves pneumatically conveying concrete or mortar through a hose at a high velocity onto a surface.

7) Injection grouting — This is a common method for filling cracks or open joints. The materials used for this method can be either cementitious or chemical.
8) External Reinforcing — This method incorporates steel elements, Fiber Reinforced Polymers (FRP), Post-tensioning cables or other materials placed outside or on the surface of structural members to strengthen them.

3. Repair Documents

On many, if not most repair projects, it is difficult to establish the exact scope of work. The documents must be structured to allow for a fair and competitive bid process and to protect the owner for negotiated projects. This can be accomplished by providing the contractors bidding the projects with specified quantities.

This requires that the specifier perform a reasonable evaluation of the existing conditions to establish the scope of work. Based on the findings, the specifier must establish quantities for each type of repair or task to be performed by the contractor. The contractors will be asked to provide unit prices for each type of repair so that adjustments can be made for the actual quantities of work performed.

The repair details provided on the documents should be for the known conditions that need repair. It is usually necessary to modify details during construction for actual field conditions, which may vary from the assumed conditions. Re-engineering during construction is not uncommon.

When deterioration is particularly severe or when extensive concrete removal is anticipated, the project documents should caution the contractor that temporary structural support should be anticipated. Special attention should be given to the structural components under repair as well as to adjacent framing. Redistribution of loading during the work should be anticipated and considered during the preparation of the construction drawings. Contingency provisions should be included in the drawings and specifications for addressing potential increases in the scope of work.

The parameters for concrete removal should be defined and, if possible, boundaries of concrete removal and replacement shown on the documents. The specifications and drawings need to establish the criteria for preparation and provide adequate information to provide a standard for acceptance.

4. Bidding/Negotiation process

The selection of a qualified concrete repair contractor is an important aspect of the repair process. Not all repair contractors are proficient in all phases of repair work. If possible, select contractors who have demonstrated competency on projects with work similar to the project being bid.

A Pre-Bid conference should be held with all of the bidders, the engineer and the owner present. This will provide an opportunity for the bidders to ask questions and to increase their awareness of the project objectives and the scope and nature of work. It is best that the meeting be held at the repair site.

Prior to the start of work, a Pre-Construction Meeting should be held which would include the owner, engineer, contractor and their project manager, superintendent, and material suppliers. The contractor should present their schedule for the project at this meeting. The frequency of meeting, field reports, submittals and other items pertaining to the delivery of the project should be discussed at this meeting.

5. Execution of work

The repair work should be executed in accordance with the project documents. Typically the documents will be based on specified quantities. It is thus important that the actual quantity of each type of work be carefully determined and documented. The owner should be informed immediately of any overruns in the specified quantities.

The repair process, especially concrete removal and reinforcing repair, may alter the load distribution of the structure and of the members being repaired. Proper shoring and bracing needs to be provided throughout of the construction.

All of the required tasks, including concrete removal and surface preparation, need to be done in accordance with the specifications and drawings and to good industry practice. The installation of materials should be done in strict compliance with the manufacturer’s instructions and the specifications.

Quality control throughout the repair process is essential to any successful project. Appropriate inspections by the engineer and/or testing/inspection agency and contractor needs to be performed on a regular basis. This should be supplemented with field testing as deemed appropriate by the engineer and testing agency.

Conclusion

Concrete repair projects are very challenging, as is true with most repair and renovation projects. It is imperative that the engineer understands the reasons which led to the damage and/or deterioration prior to developing a repair program. The underlying causes should be corrected, although this is not always possible. As a minimum, all unsafe conditions must be corrected, and if necessary, temporary shoring or bracing provided, as soon as they are identified.

The owner must be included when formulating a repair program, especially determining the project objectives. Because budget constraints often control the approach to a repair program, it is important that the owner has a clear understanding of what is being done. Furthermore, the owner should be apprised of the anticipated life of the repairs and the long-term costs to maintain that structure, after the repairs are implemented.