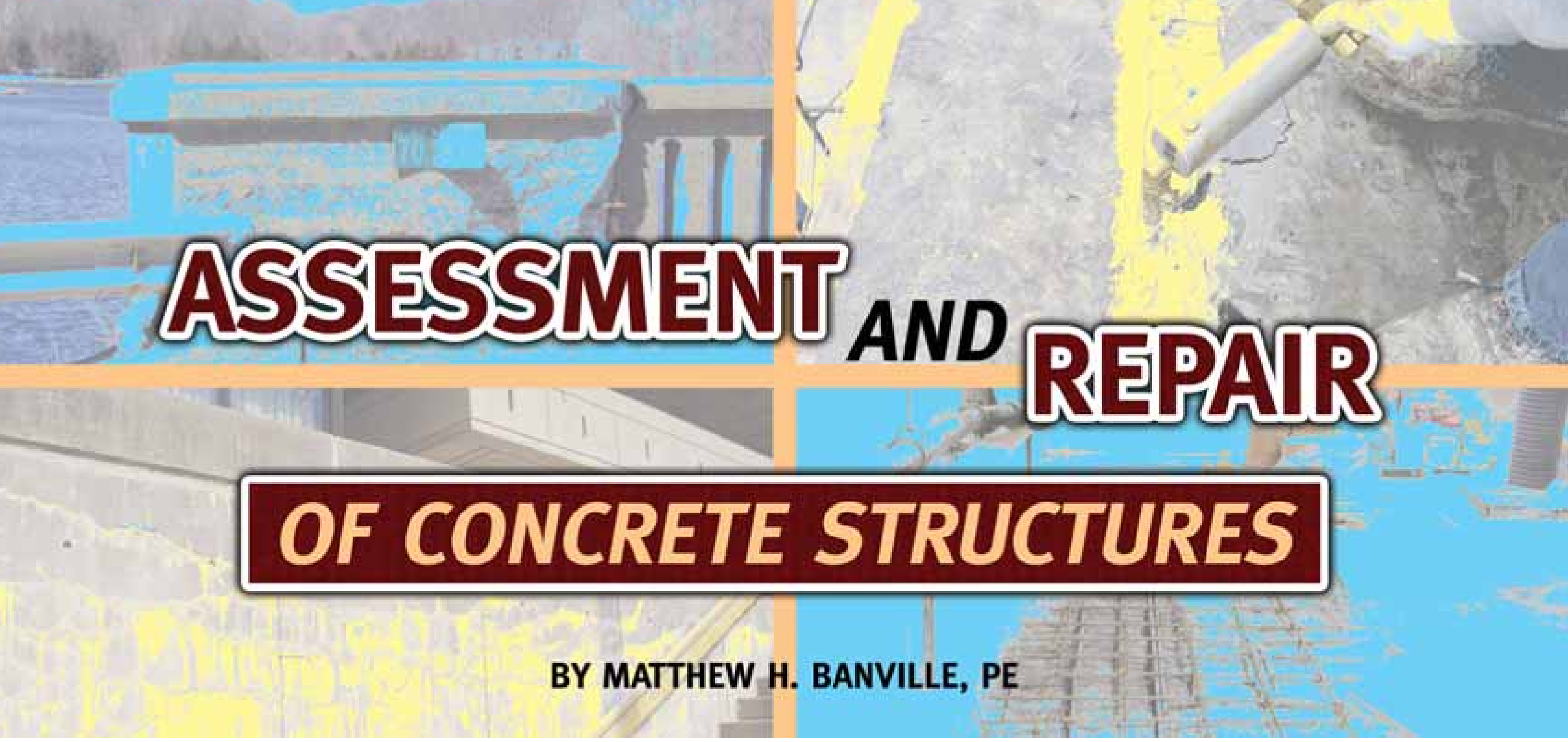

ASSESSMENT AND REPAIR OF CONCRETE STRUCTURES

BY MATTHEW H. BANVILLE, PE

Concrete–the precise combination of cement, sand, and aggregate–produces a building material that is both ubiquitous and integral to the constructed world. Long known for its compressive strength and durability, concrete attained a greater importance in construction with the advent of reinforced concrete in the latter half of the nineteenth century. The compressive strength of concrete, combined with its ability to act as a support matrix to bond to and protect the embedded steel, results in a composite that exploits the best features of both materials.

In flexure, the externally applied load is resisted by internal stresses that create a force couple between tensile forces within the embedded steel and compressive forces developed within the concrete. In compression, the reinforcing steel serves the dual purpose of strengthening, through the inclusion of longitudinal reinforcing, and confinement, through the inclusion of transverse bands or ties that restrain the concrete's tendency to expand. Through proper placement within the cross-section, building elements that exploit both the flexural and compressive properties of reinforced concrete can be constructed.

Photo 1A – Corrosion of embedded steel

As strong as reinforced concrete can be, it also possesses several weaknesses that can contribute to premature failure. If installed incorrectly or without proper maintenance, the useful life of concrete is greatly decreased. Weaknesses can be chemical or physical, and can be internally or externally applied. This paper will describe the causes of concrete deterioration and how to evaluate and repair the damage.

DETERIORATION MECHANISMS

Most people can identify the basic problems observed in concrete structures. A crack in a floor slab, a spall at the base of a column, or rust stains that discolor the underside of a beam are conditions present in many structures built with reinforced concrete. Determining why these deficiencies are occurring can be the difficult part. By understanding the ways in which concrete can deteriorate, one can deduce the cause of the sustained damage, determine the necessary remedial measures, and reduce the potential for future deterioration.

Deterioration can be caused by an attack of the chemical makeup of concrete or from chemical reactions with embedded steel. Some of the different types of chemical attack include:

- **Corrosion.** Corrosion occurs from an electrical reaction within the concrete matrix. Exposure to oxygen and moisture are required for corrosion to occur. The electrical reaction causes the iron in the steel to oxidize. As the iron oxidizes, expansion inducing tensile stresses in the surrounding concrete. When the tensile strength of the concrete is exceeded, the concrete fails with a crack or spall. The alkalinity of the concrete normally protects the steel by significantly reducing the rate of corrosion; however, open cracks, reduction of concrete alkalinity, exposure to corrosive chemicals, and

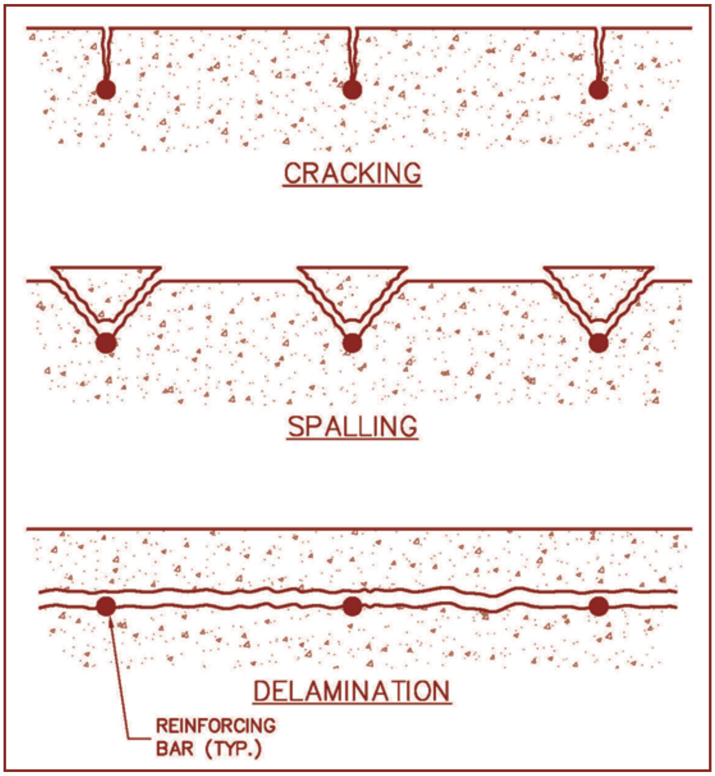

Photo 1B – Common failure mechanisms

dissimilar metals can all increase the rate of corrosion. (See *Photos 1A* and *1B*.)

- **Chlorides.** Chlorides are normally introduced to concrete structures through deicing salts or seawater. The chlorides penetrate the concrete, eventually making contact with the embedded steel. Once the chlorides combine with oxygen and moisture, corrosion of the steel occurs. With the presence of chlorides, the corrosion process is more aggressive, occurring even with high alkalinity and accelerating the corrosion process in concretes in which the alkalinity is reduced. (See *Photo 2*.)
- **Carbonation.** Carbon dioxide in the air can react chemically with cement paste when moisture is present. The resulting chemical reaction reduces the pH of the concrete. The carbonation process penetrates the pores of the concrete, eventually penetrating to the embedded steel, increasing the potential for corrosion. Since the carbonation process penetrates the concrete, open cracks will accelerate the depth of carbonation penetration. High-quality concrete is less susceptible to the carbonation process.
- **Alkali-Silica Reaction.** Because of the intimate interaction between the cement paste and the coarse aggregate, using compatible materials is important. When certain types of aggregate are used, the silica in these stones can react with the hydroxides in the cement paste. The potential reactivity of suspect aggregate can be determined through ASTM C 289 (*Standard Test Method for Potential Alkali-Silica Reactivity of Aggregates [Chemical Method]*) or ASTM C 1260 (*Standard Test Method for Potential Alkali Reactivity of Aggregates [Mortar-Bar Method]*). When this chemical reaction takes place, a gel develops on the aggregate surface. When moisture is introduced to the gel, the gel reacts by expanding and inducing tensile stresses in the cement paste, causing cracking. The cracks allow additional moisture to enter the concrete, accelerating the reaction. Alkali-silica reaction is observed on the surface of the concrete by severe map cracking on the exposed surfaces. (See *Photo 3*.)
- **Freeze/Thaw.** Freeze/thaw is the process that occurs when moisture within the pores of concrete freezes and expands. The expansion causes tensile forces to develop within the cement, causing cracking and scaling of the concrete. For freeze/thaw to occur, both moisture and freezing temperatures must be present. Freeze/thaw damage is exacerbated when the concrete is exposed to cyclic freezing and thawing. Freeze/thaw is resisted in concrete through air entrained into the concrete mix. Entrained air is the presence of large amounts of equally spaced microscopic air bubbles within the concrete mix. The freezing pore water expands into the spaces provided by the air bubbles. (See *Photo 4*.)
- **Chemical Attack.** Due to the alka-

Photo 2 – Spalling of concrete due to chloride attack of embedded reinforcing steel

Photo 3 – Alkali-silica deterioration of parapet wall

line nature of concrete, there are numerous chemicals that can react directly with the cement paste. The most common chemicals are acid and salt solutions. These chemicals may also react with certain aggregates, resulting in aggregate deterioration.

Photo 4 – Freeze/thaw damage to a bridge wing wall

Concrete is also subject to physical attack. Physical attack can originate from a number of sources, ranging from environmental effects to construction defects. Some of the different types of physical attack are as follows:

- **Thermal Effects.** As concrete is heated and cooled, the mass can expand and contract. If this movement is not accounted for, cracking can develop when a warm mass is cooled. Excessive compressive stresses may develop when a restrained concrete mass expands due to rising temperatures, potentially producing spalls and cracks. Thermal effects can also be found in structures that are exposed to differential temperatures. For example, a concrete bridge may develop cracks due to differential thermal movement when the top surface is heated by the sun, but the temperature in the cool, shaded underside changes only minimally. In this case, the upper layer of the concrete is trying to expand, while the lower layer is not. These expansive forces may induce cracking in the lower layers if the tensile stresses in the concrete are excessive.
- **Shrinkage Effects.** Freshly placed concrete shrinks as part of the curing process. This is known as drying shrinkage and is a result of water evaporating from the mix as it cures. Shrinkage can also occur when rapid evaporation of water in placed concrete results in differential shrinkage of the member; this is known as plastic shrinkage. Slabs placed in hot weather are most susceptible to this phenomenon where the curing process has begun and water can readily evaporate from the slab surface. The upper layer of the concrete then shrinks at a faster

rate than the lower layer, resulting in the development of cracks in the upper layer.

- **Loading Effects.** When a reinforced concrete member is overloaded or when the design load is applied with an inadequate amount of curing time, damage to the concrete may occur due to these loads. The result of excessive or early loading is often represented by cracks developing in the tensile zone of the member or with shear cracking developing where the shear capacity of the beam was exceeded.
- **Honeycombing.** Honeycombs occur when the cement paste does not fill the voids between the aggregate. Common causes of honeycombing include inadequate consolidation or vibration during placement, improper placement of the concrete, improper spacing of the congested or improperly spaced reinforcing steel, excessive mixing of the concrete, and low workability of the concrete.
- **Segregation.** Separation of the concrete components is called segregation. It refers to the process in which the aggregate separates by size and weight. The larger aggregate collects at the bottom of the section, and the cement paste collects at the surface. Segregation can be attributed to a high concrete slump, improper placement procedures (dropping concrete from an excessive height), and over-vibration of the placed concrete.
- **Cold Joints.** When concrete pours are interrupted intentionally or unintentionally, full concrete strength and continuity may not occur between the mating concrete surfaces. Intentional examples of this condition include structures where multiple lifts of concrete are required (e.g., tall walls); unintentional examples include delivery delays during the placement operation. For proper bond between the two pours, the mating surfaces of the joint must be properly prepared. When not properly prepared, these joints provide sources of moisture intrusion into the concrete section, possibly permitting direct attack of the reinforcing steel.
- **Placement of Reinforcing.** The placement of reinforcing steel within a concrete assembly can affect the concrete's ability to properly bond to and protect the reinforcing steel. Examples of this condition include placing reinforcing without adequate concrete cover for the service environment, placing reinforcing without proper spacing, and not accounting for lap splices. Inadequate cover can accelerate the rate of a chloride attack or the effect of carbonation. Cracks may develop in the concrete, either through improper design or construction practices, if the reinforcing is not located at the proper location.
- **Construction Tolerances.** All construction requires tolerances to achieve acceptable structures using a reasonable amount of time and effort. Extraordinary tolerancing of a structure requires precise planning by the designers and careful execution of the work by the contractor. In instances in which tolerances are not adhered to, the as-built condition may affect the strength and durability of the structure. For example, improper slope in a floor slab may permit the collection of surface runoff that is prevented from reaching an area drain. In this instance, not only is the concrete surface exposed to a direct and possibly cyclic moisture source, the unintentional collection of water may affect the response of the supporting structure and induce flexural cracking. In another instance, tied rebar assemblies may not maintain an adequate amount of concrete cover if excessive form deflection occurs during concrete placement. These deficiencies will reduce the ability of the concrete to protect the embedded reinforcing, possibly accelerating the deterioration of both the reinforcing and the concrete.

FIELD CONDITION SURVEY

It is important to research a building's history before performing the field evaluation. The plans, specifications, as-builts, and any other pertinent construction documentation will provide a description of how the building is constructed, the strengths of the materials used, and the intended purpose of individual building components. This information, combined with information on previous repairs and additions, can assist with assessing the in-use loading conditions for comparison to the design intent for altered structures experiencing distress. Repair and maintenance history information, obtained either through records or through interviews with the building owner and maintenance staff, is also useful in researching recurring problems and for understanding new problems that could be a result of improper repairs and maintenance.

If some or all of the information described above is not available, it can be attained through a number of different sources. Interviews with the building owner and maintenance staff can be helpful if there are long-term personnel on the maintenance staff. Historical records, such as photographs, are helpful in identifying changes to the building. Tax and building-inspector records can also provide a history of the permitted alterations. Reviewing the construction drawings and/or examining the structure will help determine the type of concrete construction. Some of the concrete configurations encountered include plain concrete, often found in footings, dams, and residential construction; cast-in-place reinforced concrete; prestressed-precast concrete; and posttensioned concrete.

During the field survey, the dimensions listed on the construction plans should be spot-checked for consistency and verification of the plans. Should plans not be available, the existing conditions will need to be measured; and the necessary plans, grid, elevations, and sections must be developed by hand. The level of detail of the field sketches will be contingent upon the level of detail required for the survey. On copies of drawings or field sketches, the existing conditions should be documented and categorized. These conditions include:

- **Cracks.** The types and widths of the cracks should be recorded. If a crack is believed to be active, a monitor may be installed to record any movement.
- **Joints.** The configurations and conditions of all joints should be recorded along with any noted deficiencies.
- **Delamination.** Areas of delamination should be identified by type (partial or full) and their depth recorded.
- **Spalling.** Locations, depths, and conditions of spall should be recorded.
- **Paste Erosion.** Paste erosion may be due to a chemical reaction with the paste or through erosion. Environmental conditions that may have had an impact on the area should be noted.
- **Water Infiltration.** Signs of water infiltration should be documented, along with whether the leaks were active at the time of the survey. Infiltration associated with rust staining or efflorescence should be identified accordingly.
- **Exposed Steel.** The extent and condition of exposed steel should be documented.
- **Corrosion.** Noted corrosion may include surface staining due to corrosion of the embedded steel and surface-mounted components.
- **Structural Distress.** Possible indications of structural distress include excessive deflection, shear cracking, tension-zone cracking, radial cracking at columns, etc.
- **Freeze/Thaw.** Areas of freeze/thaw damage should be identified and the depths of the damage recorded.
- **Alkali-Silica.** Areas of alkali-silica damage should be identified. Alkali-silica damage should be sampled for confirmation of the condition through laboratory testing.
- **Organics.** Organic matter growing on concrete surfaces is often indicative of excess moisture. Both the moisture and organic growth can deteriorate the concrete. Organic growth may also obscure damage to the concrete. The area should be carefully reviewed for signs of concrete distress.

Any previous repairs should be documented, including if the repair coincides with an observed defect. General conditions of the facility should also be documented. The locations, conditions, and configurations of any surface treatments, equipment, fixtures, and utilities should also be documented.

TESTING

Field Testing – Nondestructive

Numerous testing options are available to assist in completing the field-condition survey. The most common method of nondestructive field testing is through a process called sounding. Sounding involves striking the concrete surface and interpreting the sound produced. Solid concrete will produce a ringing sound, while concrete that is spalled, delaminated, or contains voids will produce a flat or hollow sound. Sounding can be accomplished using a vari-

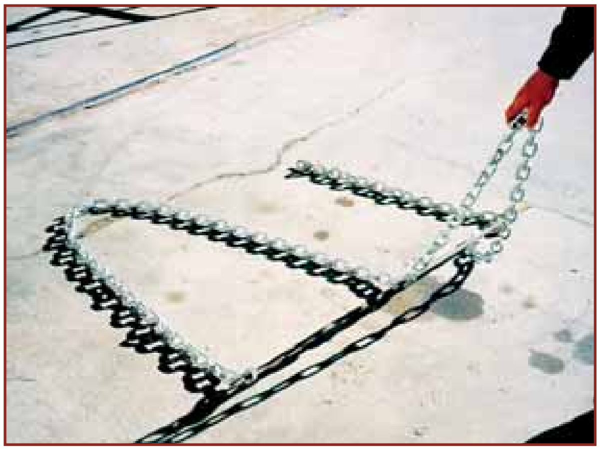

Photo 5 – Sounding of concrete by chain dragging

Photo 6 – Sounding of concrete by striking with a hammer

ety of tools. Sounding of small areas and vertical or overhead structural elements is best achieved by using a hammer or steel rod. A steel chain can also be dragged over the surface under evaluation. This method is best suited for slab surfaces where large areas can be tested in a reasonable amount of time. (See *Photos 5* and *6*.)

Nondestructive evaluations can also be accomplished using ultrasonic methods. Two common approaches include a pulse velocity meter and an impact echo system. The pulse velocity meter can detect defects such as the depth of cracks and loss of bond. The impact echo system can detect the thickness of a thin concrete section, locate a crack within the concrete, and locate voids or defects such as honeycombing.

Should the approximate size and location of the embedded reinforcing steel be desired, nondestructive testing methods include ground-penetrating radar and magnetic testing using a pachometer. While both systems result in identifying the size and location of embedded reinforcing, the ground-penetrating radar also provides a three-dimensional representation of the concrete, identifying the differing layers of reinforcing.

Field Testing – Destructive

Destructive testing methods include exploratory openings, corings, and pull-out testing. Exploratory openings can reveal conditions such as depth of cracks, delamination, reinforcing size, and pattern and coating information. Cutting an opening in the area of a previous repair will reveal information about the preparation, application, and performance of the repair.

Corings will determine conditions similar to exploratory openings but on a limited scale. Corings can provide insights into depths of cracks, depths of delamination, and reinforcing sizes. A core can also be sent to a laboratory for petrographic analysis.

Pull-out testing can determine the bond strength between a coating and the concrete substrate or between two cementitious materials. The application of this test when used for determining coating bond is covered by ASTM D 4541, *Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers*. The test method calls for bonding a plug to the surface coating. The area around the plug is then cut away to isolate the bond area. The testing apparatus is set over the plug and attached to the plug. A force is applied through the testing apparatus until the plug is pulled from the substrate. Review of the plug will reveal the type of failure (i.e., failure in the topping, along the bond line, or in the substrate). An approximation of the bond strength can be determined through a reading on the apparatus; however, this value is a qualitative answer, since different apparatus types will yield different results.

LABORATORY TESTING

Three common laboratory tests that provide concrete property information include the chloride ion content test, depth of carbonation test, and concrete petrography.

Chloride ion content is determined by an analyzer that measures the amount of chloride ion in a prepared sample. The sample is prepared from pulverized samples of concrete taken directly from the field or prepared in the laboratory from a solid sample. The application of this test is covered by ASTM C 1218 – *Standard Test Method for Water-Soluble Chloride in Mortar and Concrete*.

Depth of carbonation is determined by applying phenolphthalein to the sample. The phenolphthalein reacts with the alkaline cement paste to turn the paste a pink color. Due to its lower pH, the carbonized concrete does not change color, allowing the thickness of the carbonized layer to be measured.

Petrographic analysis involves cutting a

Photo 7 – Properly prepared surface repair

concrete sample into thin layers and observing them under a microscope. The aggregates and cement paste are examined for conditions such as mix proportions, type of aggregate, air content, presence of deleterious chemicals, alkali-silica reaction, freeze/thaw action, and depth of carbonation.

METHODS OF CONCRETE REPAIR

Concrete Removal

Prior to repairing the deficiencies observed during the field-condition survey, the damaged concrete must be removed. Concrete removal is achieved through a variety of methods, depending upon the repair to be made.

When dealing with large surface areas, scabbling, scarifying, or hydrodemolition will remove concrete. A scabble removes the deteriorated concrete by pulverizing the concrete's surface with cylinders driven by compressed air. Scarifying removes concrete by scraping the surface of the concrete. Hydrodemolition erodes the concrete by using high-pressure water jets. With hydrodemolition, the amount of concrete removal is determined by the pressure of the water jets in combination with the speed of the tractor pulling the jets.

When a more controlled or deeper area of concrete requires removal, hand-operated pneumatic hammers or truck-mounted hydraulic hammers can remove concrete by driving a chisel into the surface, causing spalling of the concrete.

SURFACE REPAIR OF CONCRETE

Shallow and deep surface repairs of concrete are prepared in a similar manner. The deteriorated concrete is removed from the area requiring repair. The area requiring repair should be overcut into a regular shape, such as a square or rectangle. The perimeter of the repair should be cut with a slight back bevel so that the repair acts like a key to retain the material. (See *Photo 7*.)

For shallow repairs, the depth to solid concrete is less than the depth of the reinforcing steel. The concrete is removed to a uniform depth. The surface of all exposed reinforcing rebar surfaces will require cleaning, most often by sand or shot blasting. For deeper repairs, where more than half of the rebar diameter is exposed, the concrete should be completely removed from around the bar so that a minimum clearance of 1 inch is provided all around the exposed bar. If necessary, in most instances, a bonding agent is applied to the steel and concrete surface. The product literature or manufacturer's representative of the product that will be used should be consulted when the suitability or need of a bonding agent is in question. Most bonding agents have specific application requirements with clear indication of the minimum and maximum exposure time before the patch material is applied. Failure to observe the manufacturer's preparation, application, and timing requirements can result in a bond break at boundaries of the patch.

There are many available repair mortars (Portland cement mortar, Portland cement concrete, shrinkage-compensating concrete, polymer-modified concrete [increases bond and flexural strength], shotcrete, etc.). Many of the available mortars contain a combination of the properties of the above-mentioned materials. The physical properties of a particular product must be carefully reviewed to ensure the necessary features are included. Since formulations vary by product manufacturer, the product literature or manufacturer's representative should be consulted.

Repair-mortar application can be accomplished in a variety of manners. Concrete can be cast-in-place, often used

Photo 8 – Epoxy injection of a concrete slab

when the full-depth repair is overhead. The repair can be hand-applied or trowelled into place; this method is often used for shallow and overhead repairs. The formed-and-pumped method works well for vertical and overhead repairs. This is when a form is applied over the repair and the repair material is pumped into the form. Each of these methods has pros and cons that must be evaluated for a particular repair.

CRACK REPAIR OF CONCRETE

The type of crack repair to be undertaken is contingent upon the objective of the repair. A crack may be repaired to restore or increase strength or stiffness, to seal against moisture intrusion and prevent corrosion, to improve serviceability, and/or to improve aesthetics.

For joints that do not require structural repair, the main purpose of most repairs will be to seal cracks against water intrusion and improve aesthetics. Repair methods that achieve this result include routing and sealing (a slot is cut into the top of the joint and filled with sealant), applying overlays, or gravity filling the crack with a flexible material.

When structural repair of the crack is required, possible repair methods include epoxy injection, gravity filling, grouting, additional reinforcing, and stitching. Both the additional reinforcing and stitching methods involve installing reinforcing. When stitching, a series of pins is drilled and epoxied over the joint. The stitches are applied in differing lengths and at various angles to prevent creating a stress plane in the concrete. Additional reinforcing can be applied either externally (through the addition of carbon or glass-fiber reinforcing) or internally (by installing pins that span the crack plane).

Epoxy crack injection is a multistep process. The crack is first sealed with an epoxy, and injection ports are installed to permit the injection process. The epoxy is then installed in a specially designed pumping apparatus that mixes the epoxy components in the proper formulation. The epoxy is then injected into the lowest or first port in the crack. The next port is monitored for evidence of epoxy exuding the tube. Once the adjacent port indicates the presence of epoxy, the first port is sealed, and the injection proceeds to the adjacent port. Injection proceeds again until epoxy is extruded from the adjacent port. This procedure is repeated until all ports have been filled. In the case of a vertical crack, the injection process begins at the lowest port and finishes at the highest port. (See *Photo 8*.)

CONCLUSION

Through proper evaluation, design, and installation, concrete repairs can be made that perform as well as the surrounding material. A comprehensive evaluation will identify the areas that require repair as well as assist in identifying possible sources of the damage. By understanding the extent and source of the damage incurred, a suitable repair using the most appropriate materials can be designed. Only through proper preparation and execution will a repair be successful. Many of the repair materials used have specific requirements that must be carefully followed to produce a quality repair.

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