



Durability of Shotcrete— Corrosion Protection

By Jonathan E. Dongell

In a prior *Shotcrete* magazine article, Spring 2015, “Durability and Exposure Conditions of Cementitious Materials – Deterioration Mechanisms,”¹ the author discussed durability as it relates to the placement environment. This article is a continuation of that topic with a basic overview of good shotcrete practices and materials and how each contributes to durability. An example of reinforcement corrosion protection is offered to show the complexities involved in creating durable concrete.

PROPER APPLICATION (EQUIPMENT)

Shotcrete requires “high” exit velocity (or shot concrete force) to create a lineal stream of material without deviation until contacting a solid form, existing substrate, or previously shot material. High velocity creates the impact force necessary for enhanced surface bonding (adhesion); mixture component bonding (cohesion); and anticipated compressive strength (compaction) to be achieved. Assuming adequate proportioning and constancy of material being shot, there is direct correlation between the material exit velocity (nozzle velocity) and the compressive strength. While a typical concrete placement relies on internal or external vibration for consolidation, shotcrete consolidation is primarily achieved through impact velocity. Of course, the use of proper equipment (pump, hoses, air compressor, nozzle, and so on) to facilitate an adequate flow of material with homogenous and uniform mixing and densification of the material is critical.²⁻⁴

QUALIFIED PERSONNEL (APPLICATOR)

In the most basic of terms, the nozzleman is responsible to ensure that the necessary in-place shotcrete characteristics for durability are maintained throughout the shotcrete placement. The qualifications of the nozzleman and the shooting practices employed must match the expertise level needed for the project. Thus, the experience and craftsmanship of the nozzleman provide the necessary workmanship for sound, durable shotcrete.

Shooting techniques consistent with sound industry practice ensure excellent compaction and consolidation, which lessens the potential for irregular trapped air pockets (or “vugs”) much larger than air-entrainment size within the shotcrete and around reinforcement.^{2,4,5}

DURABILITY BY PRESCRIPTION (QUALIFYING THE MATERIALS)

As with any concrete, it is important to use only sound, proven materials (cement, aggregate, sand, pozzolan, polymers, additives, and water) for shotcrete. Each of these materials has at least one ASTM standard that qualifies its use for shotcrete placement of concrete. Proper proportioning of these materials is critical to the shotcrete application. Proper wet- and dry-mix aggregate gradations and mixture designs are addressed in ACI 506R-16, “Guide to Shotcrete.”⁶

DURABILITY BY PERFORMANCE (QUALIFYING THE APPLICATION)

The most commonly used acceptance and performance testing criterion for shotcrete is compressive strength testing (ASTM C1604) in conjunction with testing that quantifies the shotcrete’s overall interconnectivity.^{7,6} Knowing the shotcrete’s overall density (as correlated by compressive strength testing) and its overall resistance to water/moisture ingress (as relayed by permeability, absorption, or diffusion testing) directly relates to the shotcreted concrete’s ability to resist most deterioration mechanisms. This in turn also provides a means to forecast shotcrete’s durability.^{2,7,8}

Several test methods have been developed and used to indicate the “apparent” interconnectivity of shotcreted concrete. Such testing includes: rapid chloride permeability (RCP); rapid migration (RM); surface resistivity (SR); boiled water absorption (BWA); and bulk diffusion (BD).^{7,9} Each of these test methods have been used to quantify or qualify the potential durability of a cementitious material by determining its ability to resist the ingress and movement of ions through the material. The more commonly used test method is the ASTM C1202 RCP Test Method. While the ASTM C1202 RCP Test Method actually measures electrical conductivity and not permeability, it serves as a rapid indicator that many Agencies use to indirectly correlate somewhat closely to long-term bulk diffusion.⁷

Other performance test methods exist for shotcrete for specific uses, placement conditions, or environments, such as bond strength, shrinkage, freezing and thawing, alkali-silica reaction resistance, and sulfate resistance.

QUALITY OF SHOTCRETE

As shown previously, it is somewhat straightforward to design and fabricate a good shotcrete pumping system and equipment to produce durable shotcrete. It is also somewhat straightforward to design and proportion shotcrete materials to be durable. However, qualifying the nozzleman's consistency of workmanship throughout a shoot remains elusive. Currently, the combination of compression testing and the ASTM C1202 RCP Test Method (or similar testing to establish shotcrete's apparent interconnectivity) are used as a rapid method of qualifying a shotcrete, and by default the nozzleman's workmanship. Knowing the overall density and interconnectivity of shotcrete reveals the rate of moisture/water ingress that facilitates most deterioration mechanisms. Ultimately, each of the aforementioned aspects of shotcreting determine shotcrete durability.

METAL REINFORCEMENT PASSIVATION

When steel is manufactured from natural iron sources, the iron is in a somewhat low energy state. An addition of energy is transferred to the iron during the melting, refining, and shaping processes during the fabrication of steel. The bound energy of pure iron (or corrosion potential) within reinforcement is higher, for example, than the iron compounds within the cement binder. This energy allows steel to be molded or stamped into various shapes and to be malleable and ductile, yet retain its shape. However, it is thermodynamically unstable for most placement conditions. Furthermore, this induced energy is not consistent across the surface of the steel. This increased energy, and the uneven energy fluctuations, would be quickly short-circuited without some type of passivation layer added to the surface of the steel during fabrication. Without a passivation coating, the resulting instability would create an energy release, allowing an electrochemical corrosion reaction to proceed. As a result, all steel reinforcement for use in construction in the United States has a passivation coating (usually an electroplated coat) applied during the fabrication of the steel.

Passivation: A condition whereby metal is in a nonreactive or "dormant" state.

For metal reinforcement embedded in shotcrete, the highly alkaline environment of the cementitious binder quickly forms an iron oxide layer through a reaction with the higher energy iron at the surface of the steel. This passivation layer protects the remainder of the higher-energy iron within the steel from entering reaction (refer to Fig. 1).

In other words, within a few days of being embedded in the hardened cement paste, some of the outer-surface iron reacts to form a stable layer of iron oxide, creating an additional passivation layer necessary to prevent further reaction or corrosion. This new iron oxide passivation layer is stable against the highly alkaline environment of the cement on one side, and against the higher-energy iron within the steel on the other side; therefore, it serves as an "insulator" against further corrosion. A demonstration of the reaction creating an iron oxide passivation layer can be seen in Fig. 2 and 3.

It is a very thin layer, yet a highly protective formation on the surface of the metal.

METAL REINFORCEMENT CORROSION

If the electro-plated passivation coating applied during fabrication of the steel, as well as the iron oxide passivation layer which formed after embedment in cement are compromised, then a short circuit can be created between two exposed areas of differing energy levels. If an electrochemical cell (or chemical "bridge") can be established, a corrosion reaction will proceed.

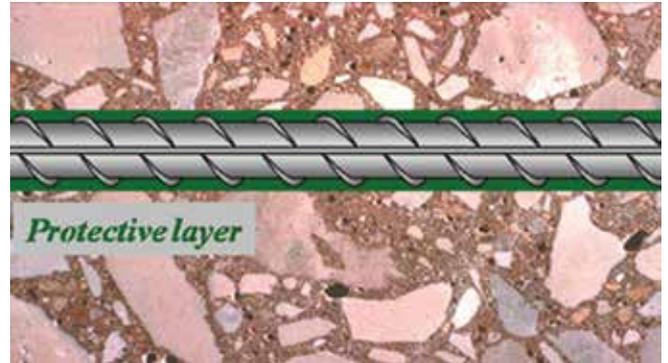


Fig. 1: Passivation (iron oxide) layer



Fig. 2: Metal plate having one end that was ground down (shiny section) to expose virgin steel



Fig. 3: Same metal plate after being halfway submerged in a high-alkaline (high-pH) water for 24 hours showing the formation of an iron oxide passivation layer (grayish-black)

In an electrochemical cell (chemical bridge), one area of the steel becomes the “anode” and another area becomes the “cathode,” and the pore water is the electrolyte.

The positively charged ferrous ions at the anode pass into the pore solution, and the negatively charged free electrons pass through the steel to the cathode. They are then absorbed by the pore solution, combining with water and oxygen to form hydroxyl ions (OH⁻). Hydroxyl ions combine with iron (II, III) ions (ferrous, ferric) to form hydrated iron (II/III) oxide - Fe(OH)₃, or “rust” (nomenclature for rust written for understanding convenience).

CHEMICAL CAUSES OF METAL REINFORCEMENT CORROSION

There are many chemicals and environments that can facilitate corrosion.¹⁰ Two of the most common deterioration mechanisms involve carbonation and chloride ingress.

Carbonation

Carbonation of the cement binder occurs due to carbon dioxide (CO₂) in the atmosphere, or contact with bicarbonate ions (HCO₃⁻) in a water-contact environment. Over



Fig. 4: Macro void space (air pocket) around reinforcement and bar termination bent upward



Fig. 5: Structural crack created pathway allowing chemical bridge to initiate corrosion

time, the compound calcium hydroxide Ca(OH)₂, which comprises between 15 and 22% of a fully hydrated cement, can carbonate to form calcium carbonate (CaCO₃). Because Ca(OH)₂ is 11.2 pH and CaCO₃ is 9.0 pH, this chemical reaction causes the pH of the overall cement binder to drop, starting from the outer surface and progressing inwards.

As CO₂ or HCO₃⁻ penetrates the cement binder system, the predominant hydroxide (OH⁻) alkalinity species within the pore solution reacts to form the carbonate ion (CO₃²⁻). This reaction forms a CaCO₃ precipitate (or solid solution) and pure water. This in turn reduces the oxygen content and lowers the pH of the pore solution, causing the loss of the iron oxide passivation layer and facilitating the electrochemical reaction that deteriorates the steel to rust.

Chlorides

Chlorides present a double threat for corrosion. Chlorides are an excellent electrolyte or conductor. Once a short circuit or chemical bridge is created, chlorides increase the corrosion reaction rate. Chlorides also concentrate at the corrosion pitting sites and form ferric chloride (FeCl₂) “rust.” Ferric chloride enters a secondary reaction FeCl₂ + 2H₂O = Fe(OH)₂ + 2HCl, which further lowers the pH of the pore solution at the corrosion pitting sites, and accelerates localized corrosion.¹¹ This double threat makes the prevention or significant slowing of chloride ingress a priority for many environments, to achieve the anticipated service life of the structure.

CORROSION PROTECTION

To achieve corrosion protection of the embedded metal reinforcement, as well as the anticipated service life of the shotcrete structure, each of the aforementioned aspects for a proper shotcrete installation are critical. This also includes sound engineering and design practices, specifying the necessary metal reinforcement and its proper installation, as well as the adequate embedment or “coverage”



Fig. 6: Insufficient coverage over reinforcement. Reinforcement bowed outward

Photo credit: Fig. 4-8 courtesy of Greg Musgrove, G & B Tile & Plaster



Fig. 7: Complete corrosion of reinforcement grid due to inadequate coverage. Corrosion reaction creates internal stress and delamination of cover material

of shotcrete based on the structure's in-service use and placement environment.

Quality shotcrete and good design practices are the key to corrosion protection and overall durability by ensuring that inadequacies (Fig. 4 through 8), such as thin concrete cover, poor compaction, high water-cementitious materials ratios (w/cm), low cement content, and poor curing conditions are avoided.

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Fig. 8: Rust bleeding through a plaster finish of a swimming pool due to reinforcement corrosion



Jonathan E. Dongell is Director of Research & Development, Pebble Technologies, Scottsdale, AZ. Dongell has worked in concrete construction and with cementitious materials spanning over 30 years. His roles have included technician, superintendent, manager, contractor, and President. He was Past President, Whitestone Cement Company, Scottsdale, AZ (1998-2005) and Universal White Cement Co, Inc., Glendale, AZ (1992-1998). He is a member and past Chair of ACI Committee 524, Plastering, and is a member of ACI Committees 201, Durability of Concrete; 225, Hydraulic Cements; 232, Fly Ash in Concrete; 308, Curing Concrete; 350, Environmental Engineering Concrete Structures; and 555, Concrete with Recycled Materials. Dongell also serves on the ACI Concrete Research Council (CRC) and the ASA Pool & Recreational Shotcrete Committee. He is a voting member of ASTM International main committees and several subcommittees, including C4.01, Cement, Lime, Gypsum, and C4.02, Concrete and Aggregates. Dongell is the author of several books, including *The Durability of Cementitious Materials in a Water Contact Environment*. He is an inventor and holds three patents on cementitious materials. Dongell is a designated expert witness in the fields of cement, concrete, stucco/plaster, and water chemistry. He was the recipient of the Del Bloem Distinguished Service Award in 2008.

*The intent of this article is to promote proper shotcrete workmanship and materials practices. While there are many products that have been shown to lessen corrosion and extend the service life (such as pozzolan, slag, densifiers, sacrificial anodes, epoxy-coated reinforcement, and many others) these were not within the scope of this article.