The Rehabilitation of Cooling Towers

Corrosion-induced deterioration of concrete caused by severe environment in natural-draft hyperbolic cooling towers

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Natural-draft hyperbolic cooling towers are extremely susceptible to corrosion-induced deterioration. Exposure conditions, and the resulting deterioration, vary depending on a host of factors. By understanding the deterioration mechanisms and the effective rehabilitation strategies, however, the life and value of natural-draft hyperbolic cooling towers can be maximized. Furthermore, due to the progressive nature of corrosion deterioration, the consequences and costs associated with delaying repairs can be significant. A variety of state-of-the-art concrete repair technologies, augmented with high-performance construction materials and protection systems, are available to implement cost-effective repair programs. These repair programs can extend service life and protect the value of the high initial investment associated with the construction of natural-draft cooling towers.

BEYOND THE SHAPE

Natural-draft cooling towers, the prominent structures used in large power generation plants, may be known for their distinct shape, but are elegant in function (Fig. 1) as well as form. The form allows for minimal operating costs compared with mechanical- draft cooling towers because no mechanical hardware in the form of fans, motors, or gear boxes is required.

Construction of new natural-draft hyperbolic cooling towers represents a large initial capital investment, so maintaining the current inventory is crucial. Process conditions, however, make hyperbolic cooling towers especially vulnerable to corrosion-induced concrete deterioration. Unfortunately, this deterioration is often either ignored or addressed with marginal repairs that perpetuate "the repair of the repair" cycle. As with any other maintenance concern, cost savings associated with addressing the deterioration sooner rather than later can be substantial. With a thorough understanding of the deterioration mechanisms and the effective rehabilitation strategies, the lifespan of a natural-draft hyperbolic cooling tower can be extended.

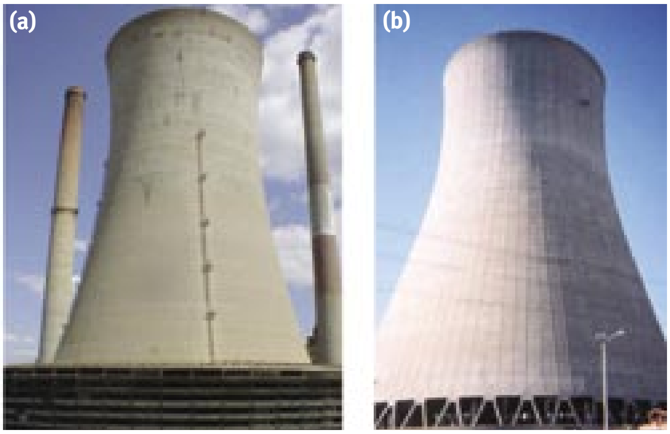

Fig. 1: Natural-draft hyperbolic cooling towers in: (a) crossflow and (b) counterflow design

CORROSION OF STEEL

Natural-draft hyperbolic cooling towers host a perfect environment for the corrosion of embedded steel, and this deterioration affects several elements in the structure. Because products formed when steel corrodes occupy more space than the parent material, they exert significant

Fig. 2: Stages of corrosion-induced concrete deterioration

tensile stresses on the concrete, causing unrestrained portions of the concrete mass to crack. Cracking allows the further ingress of elements (such as chlorides and water) that fuel the corrosion process. As corrosion continues, delamination—a separation within the concrete that usually originates at the level of the reinforcement—occurs. Furthermore, spalling can occur along the deterioration curve. Figure 2 presents the different stages of corrosion-induced concrete deterioration.

According to ACI 222R-01,[1] "Protection of Metals in Concrete Against Corrosion," "under some conditions a water-soluble chloride content of as little as 0.15% (by weight of cement)…is sufficient to initiate corrosion of embedded mild steel in concrete" while in the presence of oxygen and moisture. Chlorides can be cast into concrete or can penetrate concrete. The influence of chlorides on the corrosion-induced deterioration of cooling towers is predicated on whether the source of processed water (used for cooling) is fresh, brackish, or marine.

Another mechanism that initiates corrosion-induced deterioration is carbonation. Carbonation is the reaction of carbon dioxide from the air with calcium hydroxide in concrete, which forms calcium carbonate. Because calcium carbonate has a lower pH (more acidic) than the parent material, it effectively "depassifies" the alkaline environment of the concrete. The typical alkaline environment of concrete causes the steel to react, forming a passive film on its surface, which inhibits further corrosion. The generally accepted pH value of 8.5[1] has been determined as a depassification threshold, below which the concrete is an "active participant" in the corrosion process. The process conditions within operating cooling towers create an environment, characterized by a combination of moist conditions and high temperatures, which promotes carbonation.

With an understanding of the causes for corrosion-induced concrete deterioration in these cooling towers, plant and maintenance professionals can employ the proper mechanisms and rehabilitation strategies for concrete shells, circumferential supporting elements, and water distribution elements.

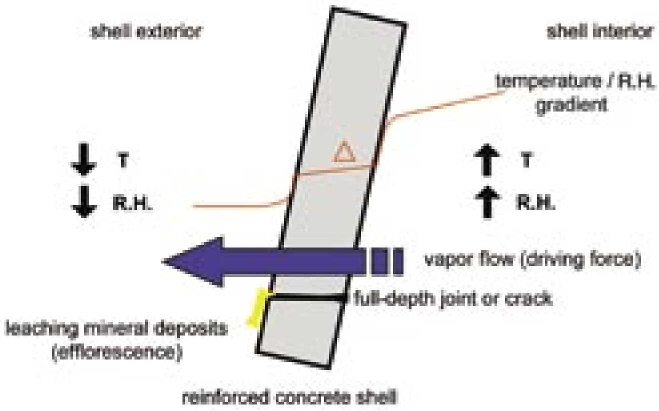

Fig. 3: Vapor flow (driving force) through joints and cracks in hyperbolic cooling towers

Note: r.h. = relative humidity; T= temperature

HYPERBOLIC SHELLS

Natural-draft hyperbolic shells are typically constructed of reinforced, cast-in-place concrete. Corrosion-induced deterioration of the concrete shell can occur both on the interior and exterior wall faces. Deterioration—in the form of cracking, delamination, and/or spalling—is typically prevalent at the throat of the shell (location of minimum radius). Extensive deterioration of the cooling tower could lead to a condition of diminished structural integrity, and delaminated concrete could pose a serious risk of falling concrete debris on operators and personnel and/or cause a release of elements anchored to the concrete.

Process conditions within the interior of hyperbolic shells are characterized by a high temperature and relatively humid environment, while conditions on the exterior of the shell are dictated by atmospheric weather conditions. Typically, the temperature and relative humidity measured inside the shell are higher than outside. As a result, water migrates across the shell cross section.[2] The driving forces for water diffusion between the inside to the outside of the shell are the temperature and humidity gradients between the interior and exterior.

As water migrates from the inside of the concrete shell to the outside, it transports mineral products, which are deposited on the exterior of the shell in the form of leachates and efflorescence. Concrete faults, such as cracks or construction joints in jump-form construction, facilitate water penetration through the shell.

Figure 3 presents the mechanism of water migration across the shell.[2] Water vapor penetration is expected to be highest at the shell throat because the velocity and density of the water vapor is highest at this location. Moisture penetration through the cross section creates an environment in the concrete throat that is conducive to corrosion of the embedded reinforcing steel.

Flue vapors exiting the cooling tower are another potential source of moisture. The vapors from neighboring cooling towers driven by wind action may even cascade onto the exterior top elevations of the shell. These vapors provide moisture for the corrosion of the embedded reinforcement at high exterior elevations of cooling tower shells.

Repair details

Gaining access to the repair areas in these cooling towers is a significant factor in the cost of rehabilitation. Intricate swing-stage setups are often required specifically to gain physical access to the positive and negative tapered sections of natural-draft hyperbolic cooling tower shells.

Surface repairs of corrosion-induced deterioration involve removal of deteriorated concrete, undercutting around the reinforcing steel, cleaning and protection of the reinforcing steel, and reestablishing the original concrete section. Form-and-place and pneumatically-applied are the two common surface repair methods employed. Because consistent material characteristics and properties are essential with these methods, the use of rapid-setting, high-quality, dense, pre-bagged cementitious repair materials from a reputable manufacturer is recommended to ensure repair success.

Using these methods, surface repair programs may be conducted while the towers are on line or off, depending on the location and extent of the deterioration. Removing extensive areas simultaneously could undermine the structural integrity of the shell and, therefore, any repair program should be carefully engineered. The depth of concrete removal should also be considered. There are certain conditions, such as in the case of slender walls with overlapping interior and exterior deterioration, for which full-depth removal and repair might be necessary. Full-depth repairs, however, are not always beneficial because they introduce full-depth joints. As described previously, flue gas is forced through these joints and can promote corrosion deterioration around the perimeter of the repair areas. Sealing of partial or full-depth repair joints should be an important consideration in the repair program.

Coating and membranes on the interior and/or exterior of the shell can provide a barrier capable of minimizing penetration of water, chlorides, and carbon dioxide to the level of the reinforcing steel. If both interior and exterior coatings are applied on the shell, the vapor permeability of the exterior coating should be considerably less than that of the interior coating to minimize debonding of the exterior coating.[3] Vapors from neighboring hyperbolic cooling towers may prevent effective application of coatings.[4]

CIRCUMFERENTIAL SUPPORTING ELEMENTS

Circumferential supporting elements for the shell typically consist of cast-in-place pedestals on the cooling tower basin, which support cast-in-place or precast diagonal columns. Many cooling tower designs also incorporate a circumferential beam at the bottom of the shell that transfers shell loads to the diagonal columns. Deterioration of circumferential supporting elements often originates at corner locations.

Circumferential supporting elements can be classified according to their environmental exposure conditions. Elements such as pedestals found within the cooling tower basin are, typically, permanently submerged. As such, these elements may have some corrosion-induced damage, but it is typically minor because steel corrodes at a very low rate due to the low availability of oxygen in underwater conditions. Columns and circumferential beams have the most aggressive exposure conditions because they are subjected to the splashing and evaporation zones. These conditions provide both a high concentration of chlorides and moisture as well as plenty of oxygen to support corrosion. Significant deterioration is often identified at the elevated regions near the shell, such as the circumferential beam and the top of the columns. This is likely a result of the high velocity draft generated by the cooling tower, which could promote oxygen and moisture replenishment to fuel corrosion.

Unfortunately, too many repair programs simply mask the problem but do nothing to alleviate the cause. For example, in marine environments, surface repairs alone may not address deterioration effectively. Typically, upon removal of all deteriorated concrete, high chloride concentrations remain in native concrete areas. Without a means to address the cause of the corrosion deterioration, extensive surface repairs alone could actually exacerbate the problem by introducing corrosion cells between steel embedded in chloride-free patch material and steel embedded in chloride-contaminated native concrete. This phenomenon is referred to as the “halo” or “anode ring” effect.

Cathodic protection has been shown to help address the cause of deterioration and is beneficial for certain circumferential supporting elements. Cathodic protection is achieved by supplying a source of current to counteract the internal current existing in the corrosion cell. During cathodic protection, current flows from an auxiliary anode material through the concrete electrolyte to the surface of the reinforcing steel, either mitigating or minimizing the corrosion process. Galvanic or sacrificial cathodic protection systems are based on the principles of dissimilar metal corrosion and the relative position of specific metals in the galvanic series. These systems do not require an external power supply and require relatively minimal maintenance or monitoring. Specifically, galvanic zinc-based, thermally applied metallic coatings provide an effective long-term rehabilitation strategy. The main advantage of these systems for this type of application is that they conform to any surface geometry or orientation.

It should be noted, however, that understanding the electrical continuity of the reinforcing steel is required for successful design and performance of cathodic protection systems for reinforced concrete structures.

WATER DISTRIBUTION ELEMENTS

Water distribution elements, typically precast structures, provide support to the fill and the water distribution piping. In a crossflow (wet ring design) construction typically consists of precast, radial, and circumferential elements stacked in several levels, while in counterflow designs, a precast structural frame within the footprint of the shell provides support for the fill and piping. Under similar exposure conditions, the level of corrosion-induced deterioration for the precast concrete elements has been found to be higher in crossflow than counterflow designs. This is because the circumferential supporting elements in a counterflow design, within the footprint of the shell, are exposed to a constant high humidity environment. For all practical purposes, under these exposure conditions, these elements can be considered to be permanently submerged. In contrast, water distribution elements with a counterflow design are subjected to splashing and intermittent wetting and drying—conditions ideal for corrosion.

Certain cooling tower designs incorporate prestressed, precast elements such as fill beams and louver panels. These elements, typically of very slender cross section, provide minimal cover to the prestressing strands and, because of the type of construction, the failure of these elements tends to be sudden. Such failures represent a serious risk of falling concrete debris and disruption to the cooling process. Collapse of fill beams at high elevations can result in failure of fill beams at lower elevations because of overload from the collapsing beams and unsupported fill. As such, prestressed concrete may not be suitable for the geometry and exposure conditions of this type of element. Other materials, such as fiberglass or stainless steel, should be considered in the replacement of deteriorated or failed elements.

IMPLEMENTING A REPAIR PROGRAM

Clearly, an environment conducive to corrosion-induced deterioration exists in the different components of natural-draft hyperbolic cooling towers. Often, the deterioration is ignored, delayed, or addressed with bandage-type repairs. Because of the progressive nature of corrosion deterioration, the consequences and costs associated with delaying repairs is significant. In certain cases, replacement of failed elements might require the use of alternative materials. Most often, however, by using state-of-the-art concrete repair technology augmented with high-performance construction materials and protection systems, cost-effective repair programs can be implemented.

Regardless of the knowledge gained in more than 100 years of reinforced concrete construction, it is crucial to recognize that concrete repair is a scientific art form that involves the use of conventional cement-based materials, as well as new techniques and materials. Understanding of the cause of deterioration is essential. A condition evaluation conducted by a team of forensic engineers and technicians is useful in locating, qualifying, and quantifying corrosion-induced concrete deterioration. Further, a variety of factors including technical (engineering), constructibility (construction methods), aesthetics (architectural), and economics (return on investment) each play a role in selecting the most cost-effect repair strategy.

Engaging specialty engineering and contracting firms that are familiar with all of the highlighted critical aspects will ensure the most cost-effective and long-lasting repairs. These repair programs can extend service life and protect the value of the high initial investment associated with the construction of natural-draft hyperbolic cooling towers.

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Selected for reader interest by the editors.

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