the complete exterior surface of each of the silo was then coated with an elastomeric anti-carbonation coating. Internal cracks were repaired with a polymer modified dry sprayed concrete.

Following occupational health and safety, quality assurance and reference assessments of several corporate contractor members of the Australian Concrete Repair Association, Buildcorp Asset Solutions (BAS) was awarded the contract to carry out the remedial works following a lump sum tender process. The client, Rio Tinto, suggested that its regular access contractor be engaged to provide full scaffolding access to the inside and out of the silos for the works. However, BAS carried out a comparative cost analysis using a specially designed mast climber system. It was found that the mast climbers offered considerable savings over the proposed conventional scaffold, not only in the area of hire and erection costs but also areas of the silo could be reached more quickly and the works completed more efficiently.

The mast climbers effectively provided a climbing workshop, fully equipped to suit the task. Six mast climbers were established on the exterior of the silos, which enabled six separate areas of the silo to be worked on at any one time, or they could be established at the same level and locked together to provide access to the entire circumference. This was particularly useful and necessary when

Figure 2: This before-and-after photo shows the silo on the left awaiting repair, while repair to the silo on the right had just been completed.

placing the 48m continuous lengths of carbon fibre laminate.

As with all sites, health and safety is of primary concern to Coal and Allied/Rio Tinto and extremely stringent safety systems were put into operation by both BAS and Coal and Allied to ensure the project remained incident free. Over 10,000 man hours were worked by crews on the project with no lost time being incurred due to injuries or health and safety incidents.

Due to the fragile state of the silos and the large amounts of concrete repair required, pneumatic hammers and other methods of demolition that would produce vibration through the structures were deemed unsuitable. Hydro-demolition was used, being far quicker and offering less vibration than conventional means of concrete removal.

Hydro-demolition was also used to prepare the concrete surface ready for the application of the carbon fibre strips. A pressure of about 83MPa applied using a rotary spray head was used to scour the surface and achieve the high bond strengths necessary for the successful application of the carbon fibre laminates.

As the remaining steel cables were fixed into position and unable to be loosened, BAS could not simply cut through them to remove them from the silos due to high tensile forces remaining with them. Numerous restraints were placed around the post-tensioned cables in accordance with a pre-calculated pattern to ensure that when cut by oxy-acetylene torches; they would simply slide back into their greased sheaths, rather than flying out from the face of the structure. The cables were cut in accordance with a well developed safe work method and removed from the work face in short lengths. ■

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Why your concrete structure fails again and again

This article looks at the pervasive problem of corrosion induced failures that plague concrete structures in many environments. It describes the common methods of addressing corrosion that are employed by structural engineers and concrete restoration contractors. This is a big problem for owners and engineers around the globe – and it is particularly vexing for those structures that are situated in high salinity coastal environments such as condominium and hotel balconies, and structures that are exposed to de-icing salts such as parking garages and bridge decks.

Ted Huck, MATCOR, Pennsylvania, USA

Concrete is the basic building block for modern infrastructure. Without concrete, the world as we know it simply would not exist. As a construction material, it provides outstanding durability, exceptional strength, is relatively simple to install, and is cost effective. Concrete, however, has its limitations and its weaknesses. To enhance the strength and mechanical properties of concrete, reinforcing steel is used for most structural applications. The quantity, spacing and physical arrangement of the reinforcing steel has a significant impact on the mechanical properties of the reinforced concrete structure.

Reinforcing steel corrodes

Unfortunately, the reinforcing steel is also the Achilles heel for concrete structures. The vast majority of concrete related corrosion problems can be directly traced to the reinforcing steel. Concrete is a porous structure – microscopic capillaries in the concrete matrix allow oxygen and water to migrate through the concrete. This is usually not a problem because concrete is a very high pH material. Typical concrete provides the reinforcing steel with a high alkalinity environment and a pH above 13. When steel is surrounded by a sufficiently high alkalinity environment, the normal corrosion reaction of steel with water and oxygen to form rust is prevented. This is called passivation – steel surrounded by normal concrete is passivated and will not react with water and oxygen to form rust.

However, when concrete is exposed to chlorides, over time the chlorides permeate into the concrete and lower the pH. When the chlorides reach the reinforcing steel, the reduced pH environment moves the steel from its normal passive state to an active corrosion state and rust begins to form. This reaction of the steel to form rust creates intense pressures as the steel expands five- to ten-fold in volume when it turns to rust. This causes delamination of the concrete, initiates cracking and eventually leads to spalling. Chlorides are ever-present in coastal environments and are commonly used as de-icing salts around the world. Chlorides can also be concentrated in many industrial cooling water applications and chemical processes.

Halting corrosion

Now that we've defined the problem, what can be done to keep concrete from failing and what can be done to address concrete once the corrosion has been initiated? While these may be related questions, the reality is that these are two different engineering problems.

The first engineering challenge is to design new structures to resist corrosion as long as possible. For new structures, there are design steps that can be taken to minimise the risk of corrosion. These steps are all geared towards the concept of keeping chlorides away from the reinforcing steel. This includes: coating the reinforcing steel; using high-density concrete to slow the permeation rate; adding corrosion inhibitors to the concrete; increasing the concrete cover over the reinforcing steel; using membranes to prevent the ingress of chlorides; and other such strategies that can greatly reduce, impede or slow down the rate of chloride intrusion. None of these, either in isolation or in combination, can completely prevent corrosion forever but they can extend the time to failure greatly thus increasing significantly the structure's useful life.

(Photos: MATCOR, Inc.)

Figure 1: Condominiums along the coast of Florida face serious corrosion issues if not properly protected.

The second challenge is how best to address corrosion for existing structures, which already have signs of corrosion or worse yet are experiencing significant corrosion issues. Once the chlorides have contaminated the concrete, there are only a finite number of approaches that can be taken. First it is important to determine the structural integrity of the concrete structure. In most cases, the corrosion can be addressed with repairs and restoration technologies. In some extreme cases, the concrete structure integrity may be so compromised as to warrant complete demolition and replacement. In the case of complete replacement, the new design should incorporate corrosion mitigation to prevent future chloride contamination.

For the majority of cases where the corrosion has not fully compromised the structure beyond repair, there are different strategies

Figure 2: Example of spalling and cracking due to concrete corrosion.

Figure 3: Reference electrode going into concrete repair patch.

that can be employed. The first such strategy is the patch repair approach. This can be done incrementally in selected areas as on-going maintenance or globally as a larger project where all areas showing the effects of corrosion are addressed.

What is important to realise is that any patch repair strategy will leave chloride contaminated concrete in those areas that are not subject to repair. Once the chlorides are in the concrete, the corrosion mechanism remains in place for further corrosion to occur – indeed in most patch and repair scenarios the next repair will not be too far away. The general rule is that the time to failure for a patch repair project is half the time from the original repair. Thus if a ten-year-old structure is showing the first signs of corrosion, it will only be five years after the first repair before a second repair cycle will be required. This is a vicious cycle of spending good money to repair the structure only to have to revisit the issue again a few years later and then again a few more years later.

A second strategy is chloride extraction. This technology can be used to remove chlorides from contaminated concrete. After completing the necessary repairs to all damaged concrete, the remaining contaminated concrete is purged of chloride ions. This involves affixing a powerful positively charged connection to the outside of the concrete structure. The chloride ions are negatively charged and when in the presence of a powerful positive charge the chlorides can actually be pulled out of the concrete structure, which can then be sealed to retard future chloride intrusion. This can provide significant life extension to a structure but is a costly process generally reserved for historic structures. It is important to remember that sealing concrete without removing the chlorides does nothing to prevent corrosion because the concrete is already contaminated. While conceptually this strategy seems quite elegant, practically it is not a viable solution for most restoration applications.

The third proven strategy to address corrosion during a repair is to install an impressed current cathodic protection (ICCP) system. Cathodic protection applies a negative charge to the reinforcing steel, shifting the potential of the steel back into the passive range despite the presence of chlorides lowering the pH around the steel. Over time the chloride ions are actually repelled from the steel by the negative charge. The simplest and most cost-effective ICCP systems for many atmospheric applications use tiny wire anodes covered with conductive coatings that can be painted over the repaired concrete. A small transformer/rectifier converts AC power to DC power to provide the negative charge. Typically these systems use very little power – not much more than a conventional 120W electric light bulb for a typical condominium balcony.

A range of decorative top coats can then be applied to meet the aesthetic requirements of the project. Other impressed current technologies and configurations can also be used to install anodes in the concrete structure including wire mesh overlays, saw slots with embedded anodes and discreet anodes drilled into the concrete structure. In some applications the anodes can actually be placed outside the concrete and effectively protect the structure.

There are a couple of technologies that are being offered in the restoration market. The first is galvanic cathodic protection, which is based on inserting a zinc anode either in the repair zone or externally to the concrete and connecting it to the reinforcing steel. These systems rely on the natural potential difference between zinc and reinforcing steel (approximately 0.7V DC) to generate the necessary negative charge to prevent corrosion. Unfortunately the resistance of the concrete is generally too high to allow sufficient current flow to achieve cathodic protection. Typical ICCP systems require 5–10V DC – a galvanic system is very limited due to its tiny voltage differential.

Another technology which is now being marketed is the use of a surface applied corrosion inhibitor. The idea behind this technology is to spray/paint the concrete surface with these inhibitors and they will migrate to the reinforcing steel, displacing chlorides and coating the reinforcing steel. Conceptually this sounds great; however, this technology is relatively new and the long-term data are not yet available to fully evaluate the effectiveness or longevity of this approach.

Conclusion

Corrosion of reinforcing steel can lead to a vicious cycle of frequent repairs. Restoration projects to repair cracking and spalling concrete where chlorides have permeated towards the reinforcing steel typically do not eliminate the underlying cause of the corrosion problem leading to future repair cycles. This does not have to be the case – technologies do exist to prevent corrosion of reinforcing steel in concrete and to end the vicious cycle of constant repairs. It is the structure's owners that have to insist on permanent solutions from their structural engineers and repair contractors. ■