Bridging the gap

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In his final article on the inspection, testing and repair of reinforced concrete buildings, Nigel Cox looks at advanced repair techniques and how they are used on everything from bridges to multi-storey car parks

Until recently, the main way to deal with the corrosion of embedded steel reinforcement has been to remove the defective concrete to expose and clean the steel, then put back new concrete.

One of the problems with this ‘traditional’ approach is the creation of ‘incipient anodes’. Corrosion is an electrochemical process which takes place at the anode, while relatively little happens in the adjacent cathode areas (see Testing concrete's credentials). Removal of the anodic corrosion area and its replacement with highly alkaline repair concrete (pH14+) can cause the adjacent cathode areas (of, say, pH11) to become the anodes.

This particularly happens when insufficient amounts of defective concrete have been broken out from the original site (often driven by a misguided approach from the surveyor who thinks that by restricting concrete break out will save his client money). This can be seen on older repairs which appear to be failing around their edges due to corrosion product being washed out. In fact, you may find the actual repair is intact but that failure is occurring at the extreme edges or within previously sound unrepaired parent concrete.

Often, this process may not occur for upwards of 15 years and thus on the majority of building façade refurbishments a client may deem that a ‘traditional’ repair is adequate.

Waterproof membranes

In structures such as multi-storey car parks, where high levels of chlorides within the deck slabs can accumulate due to waterproof membranes not being used at their construction stage, the problem of long-term control using ‘traditional’ techniques is more pronounced. The chlorides are predominantly brought in by vehicles during the winter (when salt is used to treat icy roads) and are well distributed throughout the structure.

Traditional techniques would require large areas of chloride-infested concrete to be removed, the steel cleaned and then the concrete replaced – this is impractical and very costly.

However, the creation of anodes and cathodes during the corrosion process holds the key to the development of advanced concrete repair techniques. As the electrochemical reaction at the cathode is relatively harmless, recent developments have concentrated their efforts on making all the embedded steel a cathode, hence the term ‘cathodic protection’. But for this to actually happen, something else needs to perform as the anode as this is where the corrosion takes place, and so we need this to be something ‘sacrificial’ that can in time be replaced. Below are the cathodic protection systems currently on the market.

Galvanic protection anodes

Fosroc Ltd developed a galvanic anode system in the 1990s which was initially designed to inhibit the problem of incipient anodes. The system is called Galvashield XP, where small
plates of zinc are embedded in a special mortar. The anodes were then attached to the embedded steel at each end of a traditional concrete repair.

The anodes would then remain dormant until conditions existed for incipient anode corrosion to happen at the ends of the traditional concrete repair. It is crucial that there is electrical continuity between the embedded mild steel and the zinc plate inside the anode. Zinc is lower down the galvanic table than mild steel, so as the corrosion process commences the zinc becomes the anode and the embedded mild steel becomes the cathode. The Galvashield unit therefore sacrifices itself over time instead of the embedded steel.

As no external current is being applied to the anode, these systems are self-regulating. As the moisture content within the concrete varies, the life of the anode can also vary depending on how hard they are working. It is therefore very difficult to predict their lifespan, but generally 10 years is reasonable, once they are active. Individual anodes cost around £35 (incl. fitting) and generally up to four/m\(^2\) of concrete surface area are needed to offer adequate protection.

The success of the XP anode led to the development of the CC anode range. The principle of galvanic cathodic protection (no external current applied) remains but rather than being placed in damaged areas, the CC anode is installed in areas already contaminated with chlorides but not showing signs of distress. This allows surveyors to consider installing the CC anode in large numbers across car park decks or in localised areas that appeared to have deteriorated following a half-cell survey.

The systems can be monitored to establish their success and, since they are self-regulating, ongoing maintenance costs are minimal. Their lifespans, costs and numbers required per m\(^2\) are similar to those of XP anode systems.

Galvanic anode systems, while relatively cost-effective and easy to install/maintain, do have drawbacks. Firstly, as the anodes are self-regulating, the sacrificial zinc element will not last particularly long in an aggressive environment. As the anodes are embedded within the concrete structure, replacement at the end of their life is difficult and life cycle costs can be tough to predict. Secondly, and perhaps most importantly, these systems are only able to inhibit and not stop corrosion as they do not fully protect the whole structure (although they were not perhaps designed in this manner in the first place).

**Impressed current cathodic protection**

The only accepted way to stop corrosion in chloride-infested reinforced concrete is by using impressed current cathodic protection (ICCP). This approach has been around for over 30 years and has been used in the concrete repair market extensively around the world including the UK, predominantly on bridge and car park structures, although it has been installed on pre-cast concrete panelling used on building façades and historic buildings.

The principles remain the same – make the embedded steel perform as the cathode with a sacrificial material acting as the anode. There are a number of anode types ranging from electrically conductive paint coatings and electrically conductive sprayed concretes, to embedded ceramic anodes and iridium coated titanium mesh (which is oversprayed with concrete).

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As each of the anode types can accommodate varying amounts of electrical current, the density of embedded steel within the structure often determines the choice of anode. Thus, a relatively lightly reinforced waffle slab deck in a multi-storey car park would use a conductive paint anode as a solution, whereas a heavily reinforced motorway bridge would require either an embedded anode or a mesh/concrete overlay anode to provide protection.

The system has a permanent electrical current applied to it, which has a number of
advantages. Chloride ions are negatively charged and therefore the negative charge passes through the embedded steel causing them to be repelled away from attacking the passive oxide layer around the steel. Additionally, hydroxyl ions are created on the surface of the embedded steel, increasing its alkalinity and helping to rebuild the passive oxide layer.

As soon as a new ICCP system is installed and turned on, half-cell readings will show a shift in potential to a more positive state. To test the system's success, it will be temporarily turned on/off to see the range of the shift in potential. If this shift is at least 100mV, it can be considered to be a success.

The ICCP system will protect the structure for at least the life of the anode, which for more heavyweight anodes can be over 30 years. Installation costs vary depending on the anode type but a typical paint anode system will cost around £150/m² of concrete surface area treated through to a mesh/concrete overlay system costing in the region of £300/m².

The main drawback of an advanced system can often be something simple. Most contracts require new systems to be maintained and monitored for at least 12 months. If clients then take on this role it is important for it to be properly managed – it is not unknown for multimillion pound installations to stop working because the electric bill has not been paid.

Other techniques
A number of other electrochemical systems exist but with varying levels of success. They are, however, still favoured by some clients.

Realkalisation/desalination
Norcure developed this system in Norway in the 1990s. Vector Corrosion Technologies in Canada now own the rights to the system. The principal is similar to ICCP but the current impressed is far greater (albeit still low in amps). Much of the chlorides are actually extracted from the concrete, hence the term ‘desalination’. Initial costs are relatively high (upwards of £250/m²) and while it is still used around the world, it never really gained acceptance in the UK. Realkalisation was a ‘sister’ technique using the same equipment to restore the alkalinity to carbonated concrete but again its high cost (£100/m²), and the restricted number of licensed contractors, killed the system off in the early 2000s.

The long-term success of both systems relied upon the source of the problem being halted or kept out. Thus, a reinforced concrete structure that had its chlorides extracted would then need to be coated to prevent future ingress unless the source of the chloride could be eradicated in another way. Likewise, a realkalised structure requires the prevention of future carbonation.

Migratory corrosion inhibitors (MCIs)
The technology for MCIs comes from the US where corrosion inhibitors (CIs) are used extensively in new builds. CIs are where aminos attach themselves to embedded steel providing a barrier against carbonation and chlorides. The problem with MCIs is the method by which the active ingredients move from the concrete surface to the embedded steel (manufacturers claim that sufficient amounts of aminos can migrate in a gaseous state).

While manufacturers have, perhaps unsurprisingly, come up with convincing evidence of their ability to inhibit (not stop) corrosion, numerous independent studies have, in my opinion, confirmed the doubts surrounding their usefulness. This however, has not stopped the materials, which are relatively cheap (£25/m²) to buy and apply, developing a ‘mature’ market in the UK.

In my opinion, they are unlikely to do much harm, or indeed much good, to your reinforced concrete structure.

British Standard EN 1504
Until recently, no British standards existed for concrete repair. Clients and surveyors often
relied on the ‘generous’ nature of materials manufacturers to produce specifications, perhaps not realising that they were effectively ‘sole specifying’. However, after many years of debate with our European partners we finally have BS EN 1504.

The objective of the standard is to provide guidance and instruction to manufacturers, applicators and designers alike. September 2006 saw the start of the compliance period and the standard became mandatory in 2008. However, even though mandatory, I have been surprised at the apparent lack of awareness of this standard among surveyors and engineers around the country. There is some catching-up to do.

British Standard EN 1504
Part 1 – deals with the definition of the euro-norm standards and largely results from the Thematic Network on Performance-Based Remediation of Reinforced Concrete Structure study.

Part 2 – refers to surface protection systems for concrete. It specifies the requirements for the identification, performance and safety of coating systems such as anti-carbonation coatings, silanes, etc. It also refers to protective systems for new concrete such as high-performance curing agents, surface hardeners, etc.

Part 3 – is split into four sub-sections categorised R1, R2, R3 and R4 referring to various repair requirements:
- R1 is a very low-level non-structural requirement for jobs such as blow hole filling, tile grouting, etc.
- R2 refers to non-structural mortars, levelling and fairing coats. To achieve R2 the materials need to pass demanding tests relating to bend strength, modulus of elasticity and strength requirements.
- R3 relates to structural lightweight or high-build mortars. These are generally used for repairs to structural concrete in dwellings such as tower blocks. Again, the test methods are very stringent and include chloride absorption rates, freeze/thaw testing, bond to substrate, etc.
- R4 deals with high-strength structural repairs. This is most relevant to bridge and highway structures, etc. The test requirements are very similar to the R3 methods but there are differences in strength gains and overall strengths.

Part 4 – refers to structural bonding products and systems.

Part 5 – refers to injection products for the filling of cracks, structural or non-structural work, including the force transmitting methods, ductile filling of cracks or voids and swelling type systems often used in place of water bars in new reservoir constructions.

Part 6 – refers to structural anchoring systems, which includes resin and cementitious anchor bars, grouts used in conjunction with concrete repair contracts and the grouting of voids.

Part 7 – deals with reinforcement corrosion protection and includes corrosion inhibitors and barrier coating systems, normally used for car park deck coatings and bridge deck waterproofing systems, etc.

Part 8 – specifies procedures for quality control methods and evaluation of conformity, including marking and labelling of products and systems.

Part 9 – relates to the specification of products and systems. It states the general principles and basic considerations of the BS EN 1504 series and should be adhered to when specifying protection and repair within plain or reinforced concrete.

Part 10 – is for repair contractors and refers to site application of products and systems and quality control.

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Further information
- Building pathology: Testing concrete’s credentials
- Building pathology: A concrete solution
- Related competencies include: T006 and T021