Cementitious mortars provide an alkaline environment to steel reinforcement should generally be specified in cases where concrete deterioration is induced by steel corrosion. To ensure good contact between steel reinforcement and repair mortars, a pre-treatment rebar coating is sometimes applied to the steel. Most pre-packaged cementitious concrete repair systems, also contain some form of coating or primer to promote adhesion between repair material and concrete substrate. These are generally acrylic-based, however epoxy bond coats are also available. It should be noted that these bond coats may impede electrochemical techniques and in-particular, epoxy-based systems may impede the desirable effect of natural moisture movement in the concrete.

5.6.3 Polymer-modified cementitious repair mortars

The most widely used materials for patch repair of concrete are proprietary polymer-modified Portland cement based mortar systems, which are designed to offset some of the limitations associated with unmodified mortars.

Applications for polymer-modified mortars are varied and commonly include use as patching material for building structures, floors, parking structures, bridges, wharves and industrial structures.

These materials offer improved bond strength, workability and curing properties, and reduced permeability. In general, the chemical resistance and shrinkage characteristics of the modified mortars are also significantly enhanced.

A wide variety of pre-packed or bagged mortars which are suitable for small repairs are readily available. These include spray-applied mortars, hand-packed mortars of varying strength grades, mortars for thin layer applications, sulfate resistant mortars, quick-setting mortars and micro-concretes used for filling larger areas.

These mortars contain a range of admixtures to allow the water cement ratio to be minimized and improve workability and placement characteristics. A key requirement of an effective repair material is shrinkage compensation, which aims to counteract the drying shrinkage effects of the patch repair. It is now common for these materials to contain fibres to improve shrinkage cracking resistance and cohesiveness. Some mortars may also be formulated with corrosion inhibitors and other additives.

In selecting the repair mortar material, it is important to ensure that it is compatible with other repair and protection methods that may form part of the repair, such as electrochemical treatments. Adherence to minimum and maximum application thicknesses is also important as this can vary between products.

In general, polymer-modified mortars exhibit good workability, weathering resistance, good compatibility with parent materials and relatively low permeability compared to other systems.

5.6.4 Ready-mixed or ordinary concrete for patch repairs

The use of unmodified cementitious repair materials, usually consisting of conventional ready-mixed concreting materials, is generally not recommended in isolation. They are often mistakenly thought to be the most economical systems available. They have the advantage of flexibility in mix proportioning to match the characteristics of the substrate concrete but are often disadvantaged by poor adherence, significant shrinkage after setting, and cracking. However, some systems may employ effective shrinkage-compensating admixtures that reduce shrinkage to an acceptable level.

To minimize shrinkage and cracking, the repair concrete or mortar should have a very low water to cement ratio and optimum coarse aggregate content. Application should be limited to situations where the original cause of concrete deterioration has been eliminated, such as physical or mechanical damage. Placing of these materials can also prove difficult due to their low water to cement ratio and aggregate size.

5.6.5 Epoxy-based repair mortars

Epoxy polymer concrete is essentially a composite of polymer binder, typically 100% solids epoxy resin, and aggregate. It is used primarily in industrial floors in Australasia, but also in highway applications, overlays and bridge decks in Europe and the USA.

Cold-curing mortars, typically two-part epoxy resins, may be used for protection and repair work only in exceptional cases where, for example—

- extremely high chemical resistance and resistance to abrasion is required;
- extremely rapid curing is essential;
- the post-treatment required for cement-bound concrete or mortar (with or without polymer additive) cannot be carried out; and
- care should be taken when selecting epoxy-based repair mortars to ensure compatible stiffness, thermal performance and fire rating of the repairs.

5.7 COATING ON STEEL REINFORCEMENT (EN 1504-9, PRINCIPLE 11)

This principle is based on the prevention of anodic dissolution of steel reinforcement by applying a suitable coating to the surface of the steel.

Under practical conditions, it might be very difficult to achieve a sufficient degree of cleanliness of the steel and an overall sufficiently impermeable and electrically isolating steel coating. Therefore the practicality of the method needs to be checked at the site under the given condition when using this repair principle.

This repair principle is also applicable to reinforcement that are less prone to corrosion in aggressive environments. The use of stainless steel and galvanized steel in repairs, as well as non-ferrous ferrous reinforcement is becoming more widespread, as it is in new construction in highly aggressive environments. The use of these alternative reinforcing materials generally increases the time to the initiation of corrosion as the materials have greater resistance to corrosion from aggressive processes, but can be susceptible to localized attack.

The principle also forms part of standard repair processes with proprietary polymer-modified cementitious coatings, including cementitious/epoxy resin hybrid coatings for reinforcing steel in concrete repair. The products claim to—

- restrict oxygen molecules reaching the embedded steel;
- prevent chloride ion access to the steel; and
- maintain the electrical potential of the coated steel equal to that of the uncoated steel in the parent concrete substrate.

The use of zinc-rich epoxy based systems, for example, has been widespread for many years. These systems are claimed to provide ‘active’ protection as well as providing the barrier effect. The active protection is provided by the zinc content of the coating which will corrode preferentially to the steel should complete passivation of the steel not be achieved or conditions in the adjacent concrete are such that corrosion can occur.

5.8 CORROSION INHIBITORS

There are a range of corrosion inhibitor products on the market. There are products which inhibit the anodic reaction (anodic inhibitors), the cathodic reaction (cathodic inhibitors) or both reactions (mixed inhibitors). Corrosion inhibitors are now routinely included in the formulation of some repair mortars and reinforcement coating systems while surface-applied products are generally termed “migrating” corrosion inhibitors.

At the time of writing it is industry-accepted knowledge that the ability of migrating corrosion inhibitors to penetrate deeply (say 30 mm or more) into the concrete is unproven. Migration of surface-applied corrosion inhibitors is considered possible to depths of up to approximately 20 mm. However, where permeability of concrete is variable, a corresponding variation in the penetration of corrosion inhibitors is also expected to occur.

Further, it is accepted that the ability of corrosion inhibitors to stifle corrosion in aggressive environments or chloride contaminated structures is limited and no reliance should be placed on their effectiveness in this situation.

5.9 CATHODIC PROTECTION (EN 1504-9, PRINCIPLE 10)

5.9.1 Introduction

Cathodic protection (CP) is an electrochemical technique used to stop or prevent corrosion occurring to the steel reinforcement. The principles of cathodic protection of steel reinforcing in concrete were adapted from those that have been used for steel structures in-water or in-ground for nearly 200 years. The design and application of cathodic protection systems for reinforced concrete structures has become increasingly more well documented, with over 40 years of favourable results around the world.

A CP system works by converting the whole of the reinforcing steel (or prestressing steel) surface into a cathodic area, hence the name, and moving the anodic reaction to an alternative material. A CP system provides protection by driving a current at least equal to the corrosion current between the steel reinforcement and the new external anode.

Cathodic protection can be applied by galvanic means as well as impressed current means. The CP anode may be a metal which is more active in the Galvanic Series of metals than iron (steel), with the current flowing due to the driving voltage from the galvanic cell formed, and the more electronegative metal corroding. This is known as galvanic cathodic protection (GCP). Alternatively, the driving voltage may be derived from an external source, such as a transformer/rectifier, in conjunction with a CP anode which corrodes only at a very slow rate. This is impressed current cathodic protection (ICCP).

Cathodic protection promotes the development of alkalinity at the steel surface and the migration of chloride ions from the steel surface toward the anode. Cathodic protection has gained very rapid acceptance since the 1980s in Australasia and many structures suffering from chloride induced corrosion are protected by cathodic protection systems.

The main technical criteria to check if cathodic protection has been achieved is if a 100 mV potential decay after 24 hours has been achieved. Various different electrochemical systems exist on the market (i.e. impressed current, galvanic and hybrid systems), however, if this criterion has not been achieved then the treatment should not be called ‘cathodic protection or CP’.

The design, material selection, installation, commissioning and monitoring of cathodic protection systems are detailed in AS 2832.5.

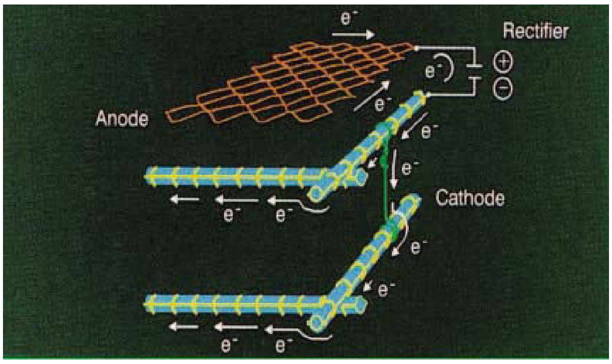

FIGURE 5.2 CATHODIC PROTECTION

5.9.2 Impressed current anode systems

There are many types of impressed current anode, and the selection of the correct one is important in determining the overall cost and durability of the system. The variability in impressed current anode types presents the CP designer with great flexibility to provide the optimum protection current at the correct locations for the desired structure life. Combinations of impressed current anodes can also be utilized to provide the most whole-of-life (life cycle) cost effective solution. Table 5.4 provides an outline of the various impressed current anode types by category (Green, 2014).

TABLE 5.4

CONCRETE IMPRESSED CURRENT ANODE TYPES BY CATEGORY

Surface applied	Encapsulated	Immersed/buried
Organic conductive coating Arc sprayed zinc Thermally sprayed titanium Conductive cementitious overlay	Electrocatalytically coated titanium mesh or grid, surface installed and embedded into cementitious overlay Electrocatalytically coated titanium ribbon, ribbon mesh or grid, embedded into cementitious grout in recesses (chases, slots or grooves) cut into the cover concrete Electrocatalytically coated titanium strip, mesh, grid or tubes, embedded into cementitious grout in holes drilled into the concrete Platinum-coated titanium rods in conductive graphite-based backfill in holes drilled into the concrete Conductive titanium oxide ceramic tubes embedded in cementitious grout in holes drilled into the concrete	High-silicon iron (with chrome for chloride environments) Mixed metal-oxide-coated titanium Platinized titanium Platinized niobium

5.9.3 Galvanic anode systems

Galvanic cathodic protection is an area of substantial growth and has become attractive because of its simplicity and low monitoring and maintenance requirements. The anode, which is commonly constructed from metal, such as zinc, is connected to the reinforcing steel and the potential difference between the zinc and the steel causes a small protection current to flow from the zinc to the reinforcing steel.

There are various galvanic anode types for the provision of cathodic current to reinforcing steel (or prestressing steel) in concrete. The extent of cathodic current provided by such anodes may not lead to CP in accordance with concrete CP standards (e.g. AS 2832.5; ISO 12696). See Section 5.10.1.

Galvanic anodes may broadly be divided into surface applied systems and embedded discrete systems. The surface applied systems achieve relatively good current distribution, however have poor adhesion in comparison to the embedded discrete systems. Table 5.5 provides an outline of the various galvanic anode types by category (Green, 2014).

TABLE 5.5

CONCRETE SACRIFICIAL ANODE TYPES BY CATEGORY

Surface applied	Encapsulated	Immersed/buried
Arc sprayed zinc	Zinc mesh within jackets	Cast zinc alloys
Arc sprayed Al-Zn	Zinc mesh in cementitious overlay	Cast aluminium alloys
	Discrete zinc anode in patch repairs	Cast magnesium alloys
Arc sprayed Al-Zn-In	Discrete zinc cylinders	
Adhesive, zinc-sheet	Discrete rolled zinc sheet	
	Discrete zinc strips	

Unlike ICCP, galvanic systems do not require external power supplies and therefore no inherent maintenance and ongoing costs. However, galvanic systems can be monitored if required to check their effectiveness.

5.9.4 Cathodic prevention

The term ‘cathodic prevention’ refers to a cathodic protection system (usually impressed current) that is installed prior to the occurrence of corrosion. This is typically done at the time of construction of the structure, but may also be done at any time in its lifecycle.

Typically, this method is only adopted where the likelihood of corrosion related damage occurring is relatively high, where the new structure would not be capable of meeting its intended design life without cathodic protection or where the cost or practicality of maintenance in the future would be prohibitive.

Cathodic prevention systems can be applied to selected elements of a structure to enhance the corrosion resistance of reinforcement to these elements or can be applied to the entire structure. Generally, cathodic prevention is applied to tidal and splash zones of bridges and wharves in marine environments.

The technique involves the application of a small electrical current using impressed current anodes that have been embedded in the concrete during construction. The basic philosophy of cathodic prevention is that a much smaller cathodic current is required to prevent corrosion compared to a higher current requirement to suppress ongoing corrosion. The cost of the application of cathodic prevention is substantially lower than the cost of the application of cathodic protection. The main reason for this is the ease of anode installation during construction.

The conditions for pitting initiation and propagation were identified by Pourbaix who during the 1970s introduced the concept of ‘imperfect passivity’ and ‘perfect passivity’ intervals. The different domains of potential are shown below in Figure 5.3. As can be seen from Figure 5.3, for cathodic prevention, a modest lowering of the steel potential can produce a significant increase in the critical chloride level. The free corrosion potential of steel ranges from –200 mV to 0 mV versus saturated calomel electrode (SCE). Pitting corrosion may take place if the chloride level exceeds 0.4% W/W cement.

If a cathodic prevention current is applied to steel in chloride-free concrete, this will allow the steel to remain passive even when the chloride reaches a considerably high content. The cathodic prevention current produces hydroxyl ions at the steel surface and causes the chloride ions to move toward the anode away from the steel.

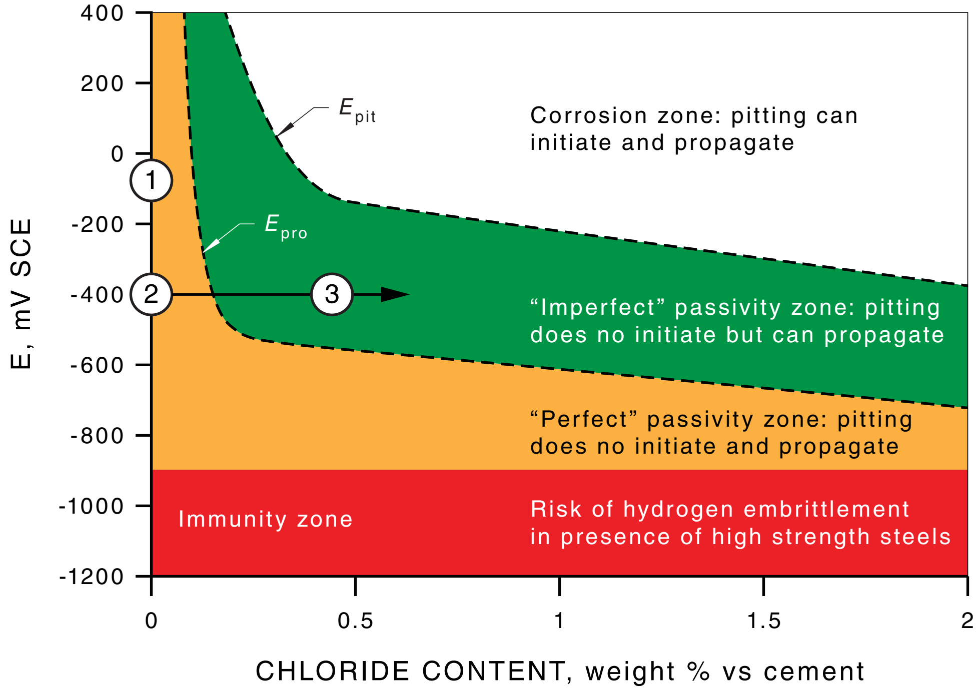

FIGURE 5.3 CATHODIC PREVENTION

When cathodic prevention is applied, the initiation of a new pit is prevented but any existing pitting can propagate. For this reason, cathodic prevention needs to be applied before corrosion initiates and then be maintained throughout the service life of the structure. If pitting corrosion has initiated, the current capacity typical for cathodic prevention will no longer be sufficient and cathodic protection current would be required.

The application of cathodic protection to prestressed elements in existing structures may cause catastrophic failure as prestressing steel is sensitive to hydrogen embrittlement. The use of cathodic prevention for prestressed steel for new structures will eliminate the risk of hydrogen embrittlement because a lower current is required to prevent the initiation of pitting corrosion. A typical operating current for cathodic prevention ranges from 3 to 6 mA/m² of steel. The cathodic prevention design current density is normally 10 mA/m² of steel surface. The design for a cathodic prevention system, system monitoring and operation is similar to impressed current cathodic protection. The main difference is related to the lower current density requirement and the ease of installation during construction.

5.10 CORROSION CONTROL METHODS

5.10.1 Introduction

Corrosion control methods are aimed at reducing the rate of corrosion. This can be achieved using varying methods. The level of deterioration of the structure, the aggressiveness of the environment and the type and design of the system determines the level of corrosion control achieved.

5.10.2 Galvanic systems

As mentioned in Section 5.8.2, a properly designed galvanic system is capable of meeting cathodic protection criteria. However, in Australasia galvanic anode systems usually refer to the use of zinc-based anodes embedded in special conductive mortar positioned around the perimeter of the repair to reduce the likelihood of corrosion initiating in the areas immediately adjacent to the repair. This type of anode has limited current output capacity and service life and normally is applied in conjunction with repair work where current density requirement is very low and it is not practical to apply an impressed current system.

Performance data from site applications suggests that it is unlikely for any of these systems to achieve the cathodic protection criteria in accordance with current standards for chloride contaminated marine structures especially in areas of high corrosion activity and with direct exposure to tidal and splash zones.

Therefore, galvanic anode systems can be considered for application under the following conditions:

- Where a permanent power supply required for an impressed current system is unavailable or is unlikely for the asset owner to maintain a monitoring program for an impressed current CP system.
- In conjunction with patch repair to reduce the effect of incipient anode.
- In structures with low chloride contamination, low resistivity and where low current density is sufficient to achieve cathodic protection.
- In structures where it is not practical to install an impressed current CP system. For instance, concrete floors in residential units affected from chloride contamination due to the installation of magnesite flooring.

The anodes are pre-manufactured and mostly supplied with integral steel wires with loop ties for tying to the reinforcing steel. The galvanic anodes are available in different dimensions and geometric shapes with varying cast zinc mass. The combination of zinc mass and surface area determines the 'strength' of the zinc anode, namely surface area determines its potential current output and mass determines its potential lifespan. The number and spacing of galvanic anodes is determined by the steel density ratio. The ratio is a calculation of the surface area of the reinforcing steel to the area of concrete.

Zinc is only activated in acidic or alkaline environments, hence the zinc anodes are encapsulated in activating media to keep zinc active over the life of the anode. The potential for the anodes to become passivated due to the pH level changing is one potential risk to their effectiveness.

It is also well documented that galvanic anodes will not work effectively in high resistivity concrete. Therefore, concrete resistivity testing needs to be carried out prior to the installation of galvanic anodes. The protective current supplied by galvanic anodes may also decrease slowly with time as zinc corrosion products accumulate.

It should be reiterated that zinc anodes used in very aggressive environments will have a relatively short lifespan, as the zinc will be consumed relatively quickly where the potential for steel corrosion is high.

Under suitable conditions however, generally when concrete resistivity and corrosion activity is low, galvanic systems for concrete atmospheric applications can provide some level of corrosion protection for a limited period of time against reinforcement corrosion. Proper investigation and design is recommended to ensure this is achievable.

5.10.3 Hybrid system

The hybrid system, which is a relatively recent development, differs from the purely galvanic systems described above. The hybrid treatment consists of a temporary impressed current followed by permanent galvanic current application. The principle of this system is that during the initial impressed current phase, corrosion pits are re-alkalized and this stops corrosion and returns the steel to a passive state. Following the application of the impressed current phase for a predetermined period, the passivity of the steel is maintained by the galvanic anode system.

The zinc anodes are installed into pre-drilled holes using embedding mortar. The number of anodes and the spacing between the anodes is determined based on the design of the system. The individual anodes are connected to the temporary power supply for the impressed current phase of the treatment. Following this, the temporary power supply is removed and the system operates as a galvanic system.

5.10.4 Realkalization (EN 1504-9, Principle 7)

Realkalization is a method used to stop and permanently prevent reinforcement corrosion in carbonated concrete structures by increasing their pH to a value greater than 10, which is sufficient to restore and maintain a passive oxide film on the steel.

Electrochemical realkalization involves a technique whereby a current is passed through the concrete to the reinforcement by means of an externally applied anode, which is attached temporarily to the concrete surface. A paste of sprayed cellulous fibre with a solution of potassium or sodium carbonate is used as the electrolyte covering the concrete surface.

The net effect of realkalization includes the effect on the concrete and on the steel reinforcement, refer Figure 5.4. The alkaline solution is transported into the concrete mass under the influence of the low voltage electrical current. This raises the concrete pH level to greater than 10. With regard to the effect on steel reinforcement the alkalinity is increased at the steel surface by production of hydroxyl ions. This reinstates the passive film of the steel, which protects against further corrosion.

The realkalization process requires minimal repair work of the concrete, especially the need to break out concrete behind the reinforcement, which is in itself a noisy, dusty and expensive exercise. The realkalization process generally takes approximately one week to complete.

There is a major advantage of realkalization over patch repair techniques in that the treatment provides a long-term solution to the entire structure treated. It will stop or reduce significantly the corrosion activity of reinforcement over the entire concrete area and not only in the repaired locations as is the case for conventional patch repair techniques.

This technique has been used widely in many countries and has a commercial track record. In Australasia, the only structures that have received realkalization treatment are the Storey Bridge in Brisbane and the Wardell Bridge in Sydney. Various trials and small applications were undertaken for various structures but the technique has not gained rapid acceptance, the main reason for this is the wide acceptance of conventional patch repair followed by the application of anti-carbonation coatings for structures suffering from carbonation.

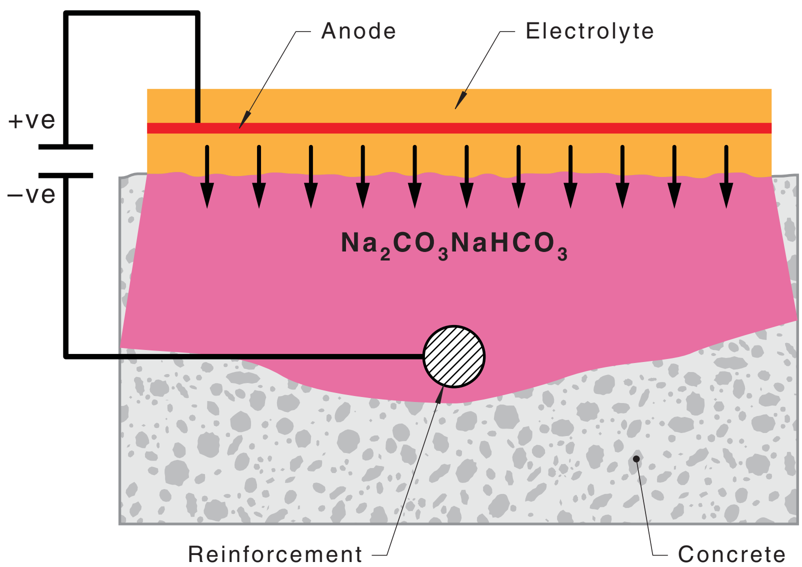

FIGURE 5.4 REALKALIZATION PROCESS

5.10.5 Chloride extraction (EN 1504-9, Principle 7)

Electrochemical chloride extraction also known as desalination or chloride removal is a method employed for reinforced concrete structures suffering from chloride induced corrosion. The system setup is the same as realkalization but the duration is typically from 4 to 10 weeks. A variety of electrolytes are used dependent upon conditions. During treatment, chlorides are transported out of the concrete toward the external electrode mesh by means of migration and are collected in the electrolyte reservoir, refer Figure 5.5. At the same time, hydroxyl ions are produced at the surface of reinforcement re-passivating the steel reinforcement.

This technique has not gained rapid acceptance in Australasia due to the fact that most of the problems associated with chloride induced corrosion are in tidal and splash zones. The application of this system is not appropriate under these conditions and ingress of chloride cannot be prevented in these areas after the completion of the chloride extraction process. For structures away from tidal and splash zones, for the prevention of new chloride ingress after the chloride extraction process, the concrete should be protected by an anti-chloride protective coating. See Appendix B for further information on repair strategies for chloride-induced steel corrosion.

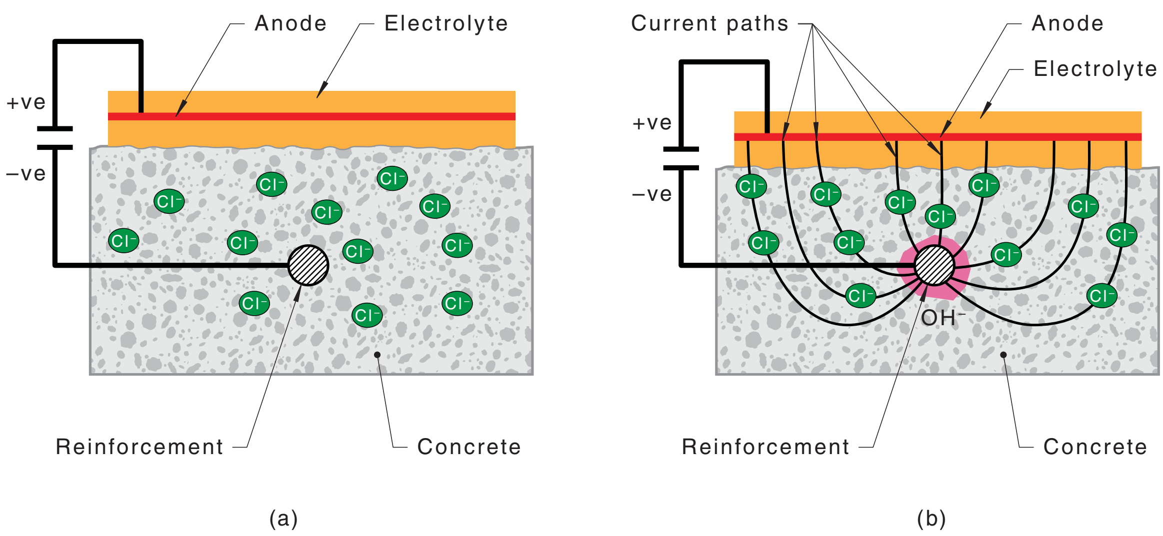

FIGURE 5.5 CHLORIDE EXTRACTION PROCESS

5.11 STRUCTURAL STRENGTHENING (EN 1504-9, PRINCIPLE 4)

Structural strengthening is beyond the scope of this document, however there are a range of methods which may be used including additional reinforcement, additional concrete sections, bonded steel plate reinforcement and the installation of post-tensioning systems to existing structures.

Externally bonded fibre-reinforced plastics (FRP), typically carbon fibre reinforced laminates or wraps are gaining acceptance for use in the Australasian market.

It should be noted these systems are not applicable for the repair of concrete suffering from deterioration due to corrosion of embedded reinforcement and should be used with extreme caution where there is a risk of reinforcement corrosion.

The technique entails bonding flexible sheets or laminates to the concrete surface using an epoxy resin. The function of the externally bonded reinforcement varies depending on the type of application, but is generally related to increasing the load carrying capacity of the structure, improving the seismic resistance of columns and beams, and stiffening of the structure. It has been used on bridges, car parks, and other structures.

FRP composite products can be manufactured and applied in a variety of ways. Resin impregnation may occur before or during manufacture. Placement techniques include manual lay-up of multiple layers of fabrics, and fibres may be unidirectional or woven mattes depending on application. Surface preparation of the concrete substrate prior to FRP composite application involves cleaning, sealing of cracks and rustproofing existing steel reinforcement. The FRP composite is bonded with the application of a resin, cured and dressed with a finish coat.

This technique has the advantage of potentially lower installation costs than other methods, on-site flexibility of use and small changes in member size after repair. The limited scope of this guide to concrete repairs does not allow for an in-depth synopsis of the material specifications, standard test methods, design/construction guidelines and performance records for the use of externally bonded FRP reinforcement. Guidance is available from manufacturers and their local representatives.

5.12 ACKNOWLEDGEMENTS

Table 5.1 and Figure 5.1 are adapted from RILEM (1994).

Table 5.3 is adapted from BRE Digest 265 (BRE 1982).

5.13 REFERENCES AND FURTHER READING

5.13.1 References

The following documents are referred to in this Chapter:

AS 2832.5, *Cathodic protection of metals*, Part 5: *Steel in concrete structures*.

EN 1504-9, *Products and systems for the repair of concrete structures,* Part 9: *Definitions, requirements, quality control and evaluation of conformity—General principles for use of products and systems*.

ISO 12696, *Cathodic protection of steel in concrete*.

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5.13.2 Further reading

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