

Factsheet 001

Carbonation and Chloride Induced Corrosion in Reinforced Concrete

1 Introduction

This document has been prepared by Moorhead Richardson to provide a simplified explanation of the effects of carbonation and chloride ingress on reinforced concrete. This factsheet will cover causes, exacerbating factors, test methods and potential remedial measures.

The explanation is 'simplified' as it does not explore the chemical reactions and equations that an in-depth study would involve.

2 Background

Reinforced concrete has proven to be an extremely durable and successful building material, partly due to the highly alkaline environment that good quality concrete provides.

The pore solution in hydrated Portland cement has a pH normally exceeding 12.6. This high alkalinity provides a thin protective oxide film on the surface of the embedded steel, which helps prevent corrosion.

A good quality concrete, of adequate cover and low permeability, additionally restricts the ingress of aggressive agents, such as carbon dioxide and chlorides, and further assists reinforced concrete durability.

3 Loss of Protection Through Carbonation

Atmospheric carbon dioxide will diffuse into concrete from an exposed surface and, in the presence of moisture, react with the hydrated cement to form calcium carbonate. The chemical reactions reduce the pH of the concrete and, over time, when the pH falls to

below 9 or 10, the protective passive film on the steel is lost and it becomes vulnerable to corrosion. This process is known as carbonation.

If the concrete cover to the steel is of consistent quality, carbonation will penetrate the concrete as a relatively even 'front' from the exposed surface inwards. It is worth noting that carbonation does not have any detrimental effect on the concrete itself and it is only when the front reaches the embedded steel that problems can occur (in the combined presence of water and oxygen).

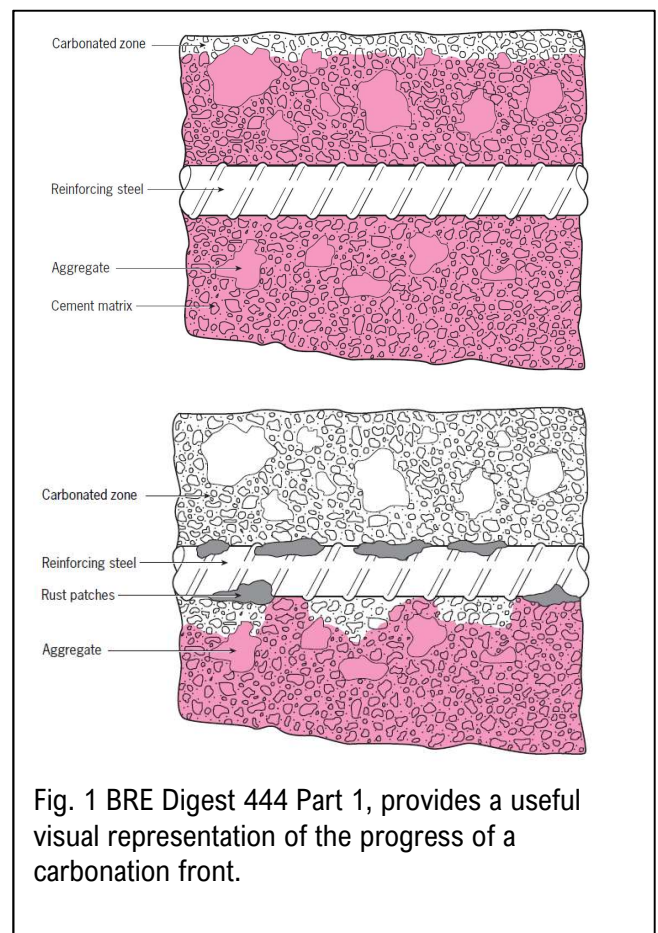


Fig. 1 BRE Digest 444 Part 1, provides a useful visual representation of the progress of a carbonation front.

4 Rate and Degree of Carbonation

The rate of carbonation penetration into concrete is affected by the quality of cover concrete and exposure conditions.

Concrete with a lower water/cement ratio will have greater strength and enhanced durability through lower penetrability of fluids.

Therefore, *concrete strength is a rough indicator for the resistance to carbonation.*

Structural concrete may be subjected to a wide variety of exposure conditions, which will impact the rate and degree of carbonation.

For external concrete faces exposed to rain the rate of carbonation penetration is relatively slower due to the moisture present in the pores forming a moist and dense carbonated zone that inhibits further carbonation progress. However, in the presence of moisture the *degree* of carbonation will be higher and the potential for reinforcement corrosion will be greater when the front does eventually reach the depth of the steel.

A case worse than exposed concrete is external concrete sheltered from rain. In these conditions, when the carbonation has reached the depth of the embedded steel, the likelihood of corrosion will remain comparatively high. However, due to lack of repeated wetting, the carbonation penetration rate is two to three times faster and therefore reinforcement corrosion is likely to start sooner.

For internal dry concrete surfaces, there is an even faster rate of carbonation, but a significantly lower *degree* of carbonation and the likelihood of corrosion is lower due to the relatively moisture free environment.

The rather complex balance between the rate and degree of carbonation, dictates that concrete elements representative of all conditions in the building should be tested.

5 Sources of Chloride

Chloride contamination of concrete may occur by them being *cast-in* during construction or by ingress during the concrete's service life.

Cast-in chlorides

In the late 1960's and early 1970's, calcium chloride was sometimes used as an accelerator in concrete mixes to reduce setting times, particularly in cold weather. It was also used in pre-cast concrete factories to produce a faster turn-around of moulds. The permitted use of calcium chloride as an additive was ended in 1976 when the effects of chloride induced corrosion became evident. Therefore, numerous structures built prior to this date, especially those that incorporate precast elements, contain cast-in chlorides.

Other sources of chloride introduced at the time of construction are some sources of aggregates (both marine and inland), contaminated water and cement. However, for modern concrete structures constructed with reasonable quality control, this is unlikely to occur.

Chloride ingress

Chloride ingress is largely a result of the use of de-icing salts (particularly for highway structures and car parks, but also footpaths around buildings). Other sources can include seawater in marine structures, airborne salt in structures in coastal towns or saline ground water.



Photo 1 Bridge piers beneath defective joints can be severely affected by de-icing salts washed through with surface run-off water.

6 Chloride Induced Corrosion

Cast in chlorides are mostly bound by the hydrating cement minerals into the cement matrix and are therefore partly immobilised. The remainder will be present as free chloride ions in the pore solution, which can stimulate corrosion.

Chlorides that have ingressed from an external source during the life of the concrete are not bound and are therefore more aggressive to the embedded steel.

While it is desirable to know the relative proportions of free and fixed chlorides, most of the criteria for corrosion activation levels are based on total chloride content.

Corrosion is an electrochemical process whereby chlorides from the pore water in concrete can cause the localised breakdown of the protective oxide film on the surface of the embedded steel. Consequently, *the chloride content at the depth of the embedded steel primarily controls the risk of its corrosion.*

Corrosion inside pits (the anodes) is driven electrolytically by cathodic reactions on the adjacent uncorroding steel area (the cathode). Because the cathodic area normally exceeds the anodic area, corrosion in the pits is intense. Under certain conditions, pits can grow rapidly to very large depths.

The presence of oxygen and sufficient quantities of free chloride ions in the pore water of concrete can produce reinforcement corrosion, even in highly alkaline (i.e. non-carbonated) concrete. However, the risk of corrosion is increased by carbonation of the concrete, which can result in the decomposition of hydrated chloride salts, liberating more chloride ions and increasing the risk of corrosion, with no change in the total chloride content of the concrete.

Even if further ingress is prevented, the process of transporting chloride ions from zones of high to low concentration may continue for months, possibly years, modifying the risk and potential severity of corrosion.

7 The Investigation

Reasons for an investigation

- A defect or deterioration has been observed (such as cracking, spalling, rust staining)
- As part of a routine maintenance programme
- There is a proposed change of use of the structure
- The ownership of the structure is to change.

An investigation to determine the extent of carbonation and chloride attack on a concrete structure can be undertaken relatively easily. Subject to access, for a typical building the site works can be undertaken in one to two days. Following the site works, there is a two-week period required for laboratory testing and preparation of the report (although this can be accelerated in urgent circumstances).

The investigation company will attempt to access a representative number of concrete components in the building and at each test location measure the depth of concrete cover to the reinforcement, determine the depth of carbonation penetration and extract a dust sample for testing in the laboratory to determine chloride content.



Photo 2 An electromagnetic covermeter is used to determine the minimum cover of concrete to the reinforcement

Depth of carbonation measurement

At the test location, a small breakout is made in the concrete, which is cleaned from residual concrete dust, to expose a fresh concrete face.

This is then sprayed with a phenolphthalein solution.

Phenolphthalein is a pH indicator that turns a bright purple at a pH level of 8.2 to 10. The depth of the carbonation is then measured as the distance from the surface of the concrete to the purple zone.



Photo's 3 and 4 Examples of surface carbonation (clear) and uncarbonated concrete (purple).

Note: Although phenolphthalein is a very useful carbonation indicator, it should be remembered that the carbonation is likely to be slightly ahead of purple 'front' as the indicator changes colour at 8.2 to 10, but the normal pH of Portland cement is 12.6.

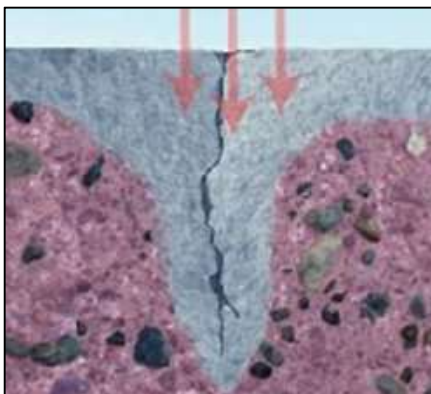


Photo 5 Surface cracks in concrete allow carbonation front to penetrate further into the concrete.

Chloride content testing

Dust samples are drilled from the concrete element (with the outer 5mm of concrete discarded to avoid contamination of the sample). The extracted samples are tested in the laboratory, with the results normally expressed as chloride content by mass of cement (typically estimated as 14% unless a cement content test has been carried out).

In locations unlikely to have had chloride ingress from an external source, i.e. any chloride is expected to have been cast-in, the dust is collected in a single sample.

Where there is the potential for chloride to have entered the concrete from an external source, such as in a car park deck or coastal structure, the dust sample is extracted in increments so that a profile of chloride content from the surface inwards can be obtained. This will provide the chloride concentration at the depth of the reinforcement and an indication of possible future levels as chloride is progressively penetrating the concrete from the surface inwards.

Locations of high chloride levels as a result of calcium chloride additives can be irregular throughout a building. For precast concrete elements, a factory running late could have added calcium chloride to a particular batch. The elements from that batch could turn up anywhere in the structure. For insitu concrete, a contractor behind schedule, or constructing in a particularly cold spell, might add calcium chloride to columns on one particular floor. This requires that sampling of concrete for chloride content must be as representative as practicable, whilst it should be understood that unless a very comprehensive testing regime is carried out, there remains the risk of some elevated chloride levels not being detected.

General inspection

As part of the site testing, an experienced surveyor will be looking out for other potentially deleterious construction materials and conditions, such as:

- High Alumina Cement (HAC) concrete
- Woodwool slabs
- Visible signs of defects (rust staining, cracking etc.)

- Concrete defects, such as honeycombing
- Areas of dampness or high humidity

These factors will have an impact on the durability of the building, and this is why it is important to use an experienced and knowledgeable team for these investigations.

8 Investigation Results

As the site testing is relatively quick to carry out, numerous locations can be tested (typically, 20 to 30, subject to access) in a relatively short time (say one to two days).

The site and laboratory testing will provide a set of results showing in each location the chloride content of the concrete and depth of carbonation penetration in relation to the depth of concrete cover to the reinforcement.

This determines the conditions at the depth of the embedded steel and allows a prognosis to

be made for the likelihood of reinforcement corrosion.

Many factors influence the rate and severity of reinforcement corrosion, such as environmental conditions, length of exposure, concrete quality and the source of contaminants. It is therefore necessary to interpret the test results in terms of the 'probability' of reinforcement corrosion occurring.

BRE has published a useful set of figures indicating the risk of reinforcement corrosion based on test results, along with prognoses and suggested repair strategies. These are shown below.

When estimating the risk of reinforcement corrosion, the future exposure conditions of the concrete should also be considered. If damp or humid conditions are introduced into a previously dry area (for example changing a 'dry' room to a kitchen) the risk of reinforcement corrosion will increase.

The figures below from the BRE show the estimated risk of steel reinforcement corrosion associated with carbonation, cast-in chloride content and environmental conditions, for differing ages of structure.

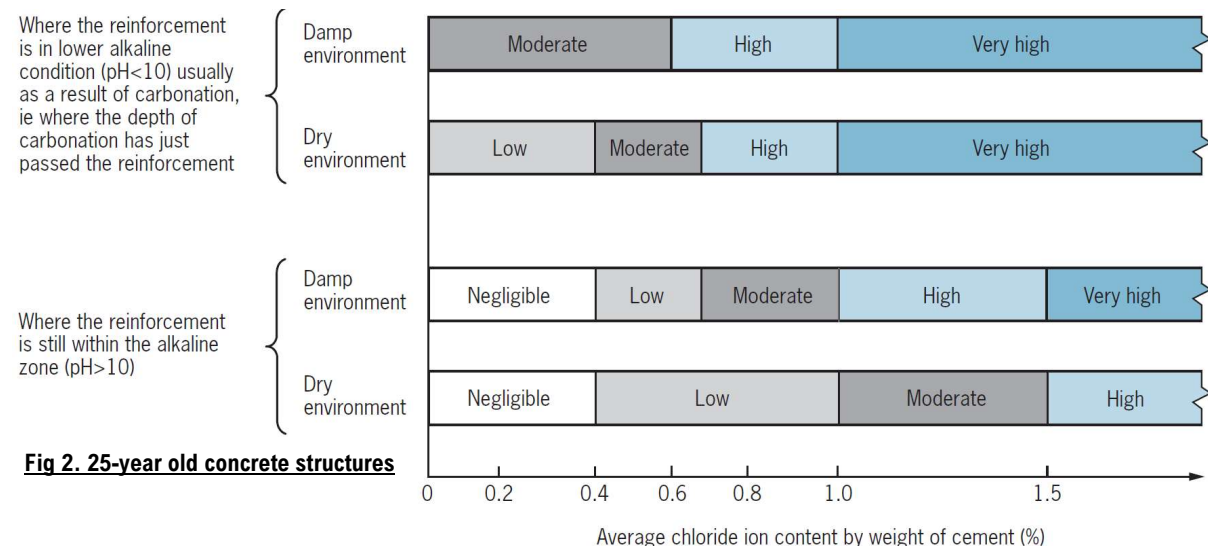
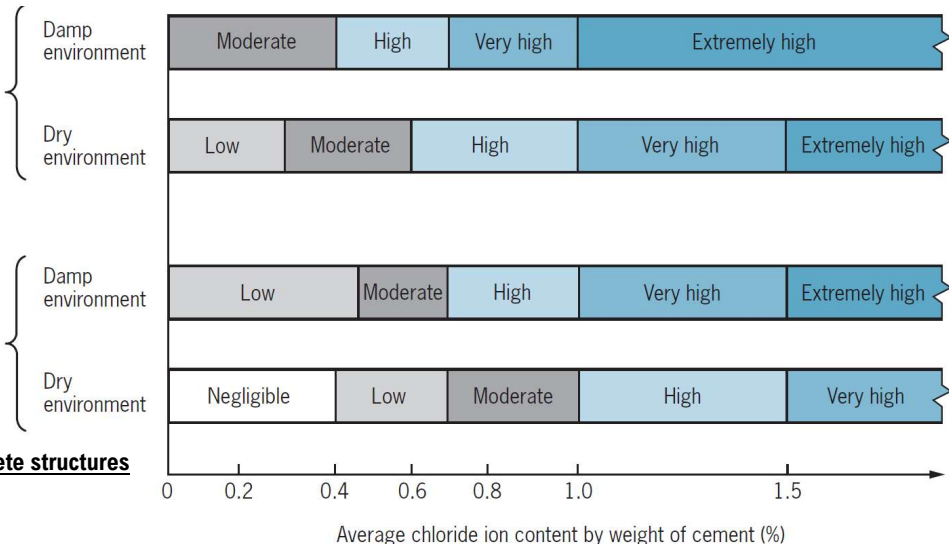


Fig 2. 25-year old concrete structures

Where the reinforcement is in lower alkaline condition (pH<10) usually as a result of carbonation, ie where the depth of carbonation has just passed the reinforcement

Where the reinforcement is still within the alkaline zone (pH>10)

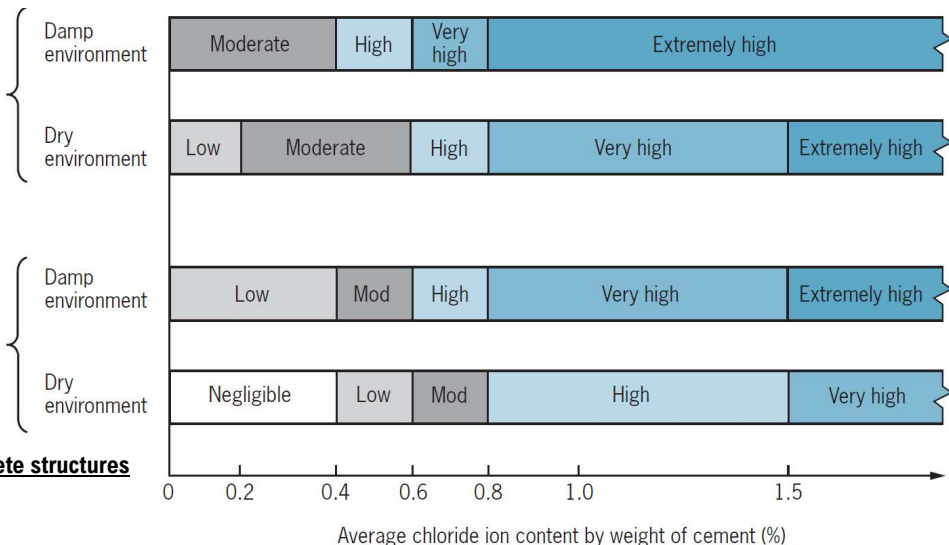
Fig 3. 40-year old concrete structures



Where the reinforcement is in lower alkaline condition (pH<10) usually as a result of carbonation, ie where the depth of carbonation has just passed the reinforcement

Where the reinforcement is still within the alkaline zone (pH>10)

Fig 4. 60-year old concrete structures



The figure below from the BRE shows an interpretation of steel reinforcement corrosion risk and prognosis based on the corrosion risk categories presented in the previous figures.

Risk category		Description	Possible action**				
Obtain risk category	Negligible	No corrosion expected	Do nothing but monitor			Feed information into model to facilitate prognosis	Choose appropriate remediation process as detailed in Part 3 of Digest
	Low	With normal maintenance no significant corrosion likely to occur. Some minor corrosion may be identified					
	Moderate	Some corrosion likely to occur. Rate of corrosion likely to be slow	Determine level of corrosion and deterioration by planned inspection appropriate to risk	Regular monitoring over time	Check present structural performance		
	High	Significant corrosion likely, particularly towards the end of the selected age					
	Very high	Significant corrosion likely over considerable area					
	Extremely high	Severe corrosion inevitable. Significant area likely to be affected					

Fig 5. Interpretation of corrosion risk

** Degree of shading reflects level of action.



Note that the above figures interpret risk based on cast-in chlorides. A separate discussion is required when considering risk due to chloride ingress.

9 Reinforcement Corrosion Effects

Reinforcement corrosion is expansive and a small amount of surface corrosion is sufficient to produce enough expansive force to crack, then spall, the cover concrete.

Once cracking develops, further routes to the steel for aggressive agents and moisture develop and deterioration accelerates.

For surveyors, the earliest sign of reinforcement corrosion is likely to be rust staining, which commonly forms a pattern that matches the alignment of the steel with the least cover (i.e. links and stirrups). This should not be confused with spot rust staining (which may be the result of pyrites in the aggregate or stray tie wires at the concrete surface) nor surface stains left from the construction process.

Degradation of reinforced concrete typically progresses with cracking, then delamination (detected by hammer tapping), incipient spalling, then spalling with exposed corroded reinforcement.

The loss of section of the reinforcing bars may have structural implications, whilst spalling concrete can have safety implications for people below.

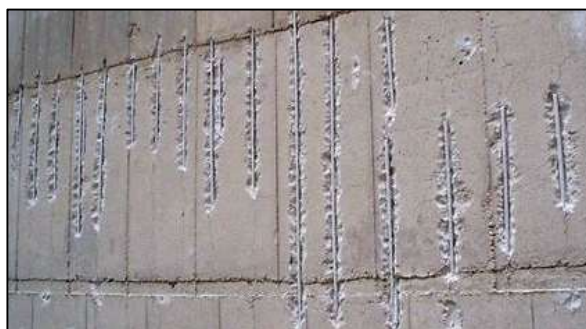


Photo 6 Typical effect of low concrete cover allowing carbonation to prematurely reach the reinforcement and cause corrosion.

10 Remedial Measures

Reinforcement corrosion on a building may be the result of a number of aggressive agents combined. When deciding a remedial strategy, it is important to have undertaken adequate testing, sampling and inspection work to determine all the factors involved.

The original investigation should have established the likelihood of reinforcement corrosion, but would not have specified the full extent or degree of deterioration.

Should the original investigation, along with visual evidence, indicate that reinforcement corrosion is occurring, it is likely that a further, more detailed, survey will be required to confirm the extent of repair works necessary. This may include more widespread testing, a full visual survey, mapping of defects and a hammer tapping survey.

Clients should be wary of non-independent companies (such as the testing department of a concrete repair firm) carrying out these surveys, as the extent of repair work recommended may be elevated beyond what is actually required.



Photo 7 Application of corrosion inhibitors to the concrete

BS EN 1504:2005 gives specifications for products and systems for the repair and protection of concrete structures. The table below refers to the Principles and Methods recommended for concrete suffering from reinforcement corrosion.

Principle	Examples of methods	Description
7. Preserving or restoring passivity	7.1 Increasing cover with additional mortar of concrete	If the reinforcement does not have adequate concrete cover, then by adding cementitious mortar or concrete the chemical attack (e.g. from carbonation or chlorides) on the reinforcement will be reduced.
	7.2 Replacing contaminated or carbonated concrete	<p>Traditionally, this is the most common repair method. It involves the careful removal of chloride contaminated or carbonated concrete from areas of cracking, delamination or spalling, and reinstatement with an appropriate repair mortar or concrete. The steel is again protected by the alkalinity of its surroundings.</p> <p>There are many proprietary patch repair materials on the market. They are either site batched or prebagged. Site batched materials are normally only used for small volume repairs. Although cheaper by an order of magnitude, site batched materials are unlikely to achieve the same level of consistency and performance as the prebagged alternatives, and should be avoided unless closely supervised.</p> <p>Prebagged repair mortars are produced under a quality assurance scheme and contain controlled proportions of specially graded sands, cements and additives that should achieve good shrinkage-compensating characteristics, very high strengths and a very impermeable cement matrix.</p>
	7.3 Electrochemical realkalisation of carbonated concrete	<p>Realkalisation of concrete structures by electrochemical treatment is a process performed by applying an electric current between the embedded reinforcement to an external anode mesh, which is embedded in an electrolytic reservoir, placed temporarily on the concrete surface. The steel (cathode) attracts the alkali metal ions towards its surface, so that high alkalinity is restored around the steel.</p> <p>Several forms of temporary anode material may be employed, such as a metal mesh or cage either positioned in a tank or bath attached to the surface of the concrete or within cellulose sprayed onto the concrete.</p> <p>This technique is applied to concrete suffering from carbonation, but it does not prevent the future ingress of carbon dioxide. So, to be effective on the long term, it also needs to be combined with appropriate protective coatings that prevent future carbonation and chloride ingress.</p>
	7.4 Realkalisation of carbonated concrete by diffusion	<p>This process can realkalise concrete that has suffered from limited carbonation by applying a thickness of fresh alkaline concrete or mortar to the surface of the concrete. The realkalisation is achieved by the slow diffusion of the alkali through the carbonated zone. This process takes a very long time and it is very difficult to control the right distribution of the material.</p> <p>After treatment, it is also always recommended to prevent further carbonation by applying a suitable protective coating. There is limited long term experience with this method.</p>
	7.5 Electrochemical chloride extraction	The electrochemical chloride extraction process is very similar in nature to cathodic protection. The process involves the application of an electrical current between the embedded reinforcement and an anode mesh placed at the outer surface of the concrete structure. As a result, the chlorides are driven out toward the surface. Once the treatment is completed, the concrete structure has to be protected with a suitable treatment to prevent the further ingress of chlorides.

Principle	Examples of methods	Description
8: Increasing Resistivity	8.1 Hydrophobic impregnation	<p>These are water repellent clear solutions sprayed on to the surface of the concrete. The pores and capillary network of the outermost layer of the concrete are lined with the hydrophobic material, but not filled. This creates a barrier to external water and aqueous solutions.</p> <p>The solutions work best on vertical surfaces where the water can run off and are not as effective barriers against standing water. Unlike crack-bridging coatings, they become largely ineffective if the concrete suffers from subsequent cracking. Such materials can be very effective when used in combination with a more conventional surface barrier system and are commonly employed as a primer in a high-performance multi-coat system. On their own, they have little or no effect on the appearance of the concrete.</p>
	8.2 Impregnation	Impregnation strengthens and reduces the porosity of concrete surface by partly or totally filling the pores and capillaries to block the pore system to aggressive agents. This treatment usually results in a discontinuous thin film on the surface.
	8.3 Coating	<p>Coatings produce a continuous protective layer on the surface of the concrete to provide a barrier to carbonation, moisture and other aggressive agents. Coatings will not resolve existing concrete durability problems and are often applied as extra protection once other remedial measures and treatments have been applied (such as patch repairs or realkalisation).</p> <p>Coatings can be applied as a preventative measure where carbonation is approaching, but has not yet reached, the depth of the embedded steel, by prevent further ingress and allowing the re-distribution of the residual alkalinity within the concrete.</p> <p>Elastomeric coatings have crack-bridging properties and can also provide an improvement in the appearance of the structure, particularly if patch repairs have been carried out.</p> <p>Some concerns with coatings include the possible masking of defects that would otherwise be apparent to a surveyor and proper application. The concrete substrate must be prepared well and be clean and dry to prevent blistering or debonding of the coating.</p>
9: Cathodic Control	9.1 Limiting oxygen content (at the cathode) by saturation or surface coating	The sprayed application of a corrosion inhibitor in sufficient quantities, or the use of coatings on the steel surface, restricts the access of oxygen to all potentially cathodic areas, to the point when corrosion is prevented.
10: Cathodic Protection	10.1 Applying an electrical potential	These are electrochemical systems that use a direct electric current flow from the surrounding concrete to the reinforcing steel to eliminate the anodic parts of the corrosion reaction and thereby decrease corrosion potential. The current is provided by an external source (Induced Current Cathodic Protection), or by creating a galvanic current through connecting the steel to a less noble / more reactive metal (galvanic anodes e.g. zinc).
11: Control of Anodic Areas	11.1 Active coating of the reinforcement	Cement based coatings containing active pigments that function as an inhibitor and/or provide a passive environment due to their alkalinity are applied to exposed steel prior to reinstatement. They are less sensitive to application defects than barrier coatings.
	11.2 Barrier coating of the reinforcement	Epoxy bases, reinforcement barrier coatings are applied directly to exposed steel prior to reinstatement. They isolate the reinforcement from oxygen or water to prevent corrosion. These applications require high levels of surface preparation and application control because the steel must be completely free from corrosion and fully coated without any defects.
	11.3 Applying corrosion inhibitors in or to the concrete	Corrosion inhibitors sprayed on to the concrete surface diffuse to the reinforcement and form a protective layer on the surface of the bars. These corrosion inhibitors can also be added as admixtures to the repair mortars.

11 Investigation Services

Moorhead Richardson is able to assist in pre-acquisition surveys and condition surveys by advising on the extent of testing required, undertaking the investigation works and preparing an interpretative report detailing the

corrosion risk based on industry standards and guidelines.

Moorhead Richardson is an independent company with no affiliation to repair companies or repair material suppliers, and therefore all advice and interpretative reporting is completely impartial.

12 References

BRE Digest 444: Corrosion of steel in concrete

Part 1: Durability of reinforced concrete structures

Part 2: Investigation and assessment

Part 3: Protection and remediation

BRE Press: Cracking in Buildings

BS EN 1504:2005: Products and systems for the protection and repair of concrete structures

BSI Standards Publication: Carbonation and CO₂ uptake in concrete (BSI PD CEN/TR 17310:2019)

Concrete Repair Association: Coating & Protecting Concrete

Concrete Society Technical Report 54: Diagnosis of Deterioration in Concrete Structures

Sika: Refurbishment, The Repair and Protection of Reinforced Concrete with Sika in Accordance with EN 1504

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Building Durability Surveys and Structural Investigations

COMPANY OVERVIEW

Moorhead Richardson is an independent company providing professional services to engineers, architects, surveyors and property owners throughout the United Kingdom.

We are experienced in surveying, testing and investigating a variety of matters on a wide range of structure type, including residential buildings, commercial buildings, factories and civil engineering structures.

SERVICES OVERVIEW

- ☐ **Structural investigation of reinforced concrete and steel framed buildings** to determine strength of materials, structural details, section sizes, foundation details, façade connection and support details, and reinforcement layout, size and type.
- ☐ **Pre-acquisition and deleterious concrete materials surveys** to determine the durability of reinforcement concrete structures prior to development, change of ownership or as part of a maintenance programme.
- ☐ **Defects and condition surveys** to determine the cause and extent of concrete deterioration in buildings, bridges and other structures.
- ☐ **Specialist concrete investigations:** high alumina cement (HAC) concrete, alkali silica reaction (ASR), sulfate attack, reinforced autoclaved aerated concrete (RAAC) and fire damaged concrete.
- ☐ **Load testing** of suspended floor slabs and beams using water tanks or weights to supplement structural calculations.
- ☐ **Bridge testing and inspection**, including half-cell and covermeter surveys, concrete sampling and testing, and post-tensioned bridge inspections.
- ☐ **Masonry wall investigations**, including endoscopic cavity wall tie inspections, brick sampling and strength testing, and mortar designation testing.
- ☐ **Leak detection** in flat roofs using a wet roof leak detector.
- ☐ **Damp surveys and water ingress investigations** using a variety of techniques, such as thermography, damp meters and simulated rain conditions.
- ☐ **Warehouse slab investigations** to determine the ability of ground slabs to support specific racking and vehicle wheel loading requirements.
- ☐ **Testing of fixings and anchors** to determine pull out resistance strength.
- ☐ **Barrier Testing** of spectator barriers in sports grounds and vehicle barriers to determine resistance to laterally applied loads.

All samples are tested in a UKAS accredited laboratory, where applicable.

Reports can be purely factual to allow the client's engineer to assess the results or interpretative with results evaluated against current British Standards and UK codes of practice.

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