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Short Guide

Historic Concrete in Scotland Part 3: maintenance and repair of historic concrete structures

HISTORIC SCOTLAND
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NATIONAL CONSERVATION CENTRE
IONAD GLÈIDHTEACHAIS NÀISEANTA

Contents

1. Introduction

This short guide, the third of three on the subject of historic concrete structures in Scotland, discusses approaches to the maintenance and repair of historic concrete. Part 1 deals with the history and development of historic concrete in Scotland during the period 1840 to 1945, when concrete progressively came into widespread use, and serves as a broad introduction to the topic of historic concrete. Part 2 provides information on the processes of decay and defects of historic concrete, together with advice on how to undertake investigation and assessment.

It is recommended that all parts of the series on historic concrete are read together, particularly Part 2 and Part 3. As concrete is often used in loadbearing building elements, specialists should be engaged to supervise any repairs undertaken, and specialist advice on the most appropriate intervention to preserve the character and structural integrity of the concrete will almost always be required.

Part 3 covers two aspects, the first of which is maintenance, which deals primarily with the routine care of surfaces, involving issues such as the treatment of minor cracks and soiling, and issues associated with the application of surface protection systems. The second aspect, repair methods and materials, addresses factors affecting the durability of the concrete.

This short guide is neither a comprehensive nor prescriptive documentation of how historic concrete should be maintained and repaired within the parameters of the conservation of historic buildings and structures. Rather it seeks to introduce the reader to the key concepts and approaches which should be considered during maintenance and repair. Concrete repair is a well-established practice in mainstream construction, and further details are provided in the references and further reading section at the end of this publication.

2. Maintenance

The prevention of concrete deterioration, as with all building materials, is generally much easier and more economic than its repair. Appropriate, regularly planned maintenance should therefore be a primary consideration. Neglecting or delaying maintenance of concrete structures can result in reduced service life and increased cost long term due to the need for future repair or replacement. If significant damage has already occurred, implementing a maintenance regime may be of little or no use.

The design of the structure and the workmanship during construction has a critical impact on its susceptibility to future deterioration. The detailing of exposed building elements is a particular concern with regard to its ability to minimise ingress of rainwater and maximise run-off. To some extent, this particular problem can be predicted at the design stage. Unfortunately, in the case of historic concrete structures design deficiencies may have already caused decay and deterioration, and life-time maintenance alone will not be able to eliminate the need for further action. A key feature of a maintenance strategy will be to assess the design features of the structure and any subsequent modifications, to identify those features that concentrate or funnel rainwater, chlorides and other environmental contaminants.

> **Inadequate design of a historic concrete structure may include:**
> - **Insufficient cover to metal reinforcement**
> - **Poor drainage leading to concentrated run-off zones and retention of chloride-contaminated water**
> - **Inadequate provision for movement**
> - **Use of inappropriate aggregates (e.g. marine aggregates)**

The most common types of maintenance include the timely repair of minor cracks and spalls, joint restoration, cleaning of concrete to remove unsightly material or deposits, and surface protection (Dupray *et al.*, 2010). Inappropriate surface cleaning and protection have the potential to cause further surface damage resulting in permanent changes to the surface appearance, its colour and texture. Surface cleaning and protection is likely to require Listed Building Consent if the structure is listed.

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The maintenance inspection should include identification of past repairs as they may have used materials and mixes that differ from the original concrete; if so, these will perform differently from the main structure and may require a more frequent inspection regime. Fig. 1 shows a listed bridge which, like all historic concrete structures, should undergo regular maintenance inspections. The repairs are self-evident.

Concrete maintenance activities are generally:

- Carried out to prevent or mitigate deterioration of the concrete
- Performed when the element is still in good or at least fair condition
- Relatively inexpensive and repeatable

Maintenance activities may include:

- Removal of surface soiling
- Minor crack repair
- Surface protection (coatings)
- Clearing blocked drainage channels and outlets

2.1 Surface cleaning

Because of its porosity, the surface of concrete is susceptible to soiling and staining by a range of contaminants such as biological growth (mostly algae), particulate and gaseous soiling from the atmosphere, efflorescence, paint, graffiti, oil and rust stains. Soiling and staining may be related to deterioration or decay, may reduce the permeability of the substrate or may simply be an unsightly surface discolouration. There is sometimes client pressure to remove unsightly stains to restore the surface appearance. However, it is often the case that a poorly considered decision to clean a concrete surface may result in permanent damage or alteration to the surface if unsuitable methods are used. Staining can be part of the natural effect of ageing, and may be considered as contributing to the structure's historic character.

Cleaning of concrete can be appropriate when there is a need to:

- **Facilitate repairs**
- **Remove staining or graffiti**
- **Remove soiling or salts contributing to decay**

The first task should be to accurately identify the causes and nature of any soiling or staining, and to consider whether, given the potential to damage the surface, the historic concrete should be cleaned at all. If cleaning is determined as being necessary then the gentlest system that achieves a satisfactory outcome should be selected. It should be noted that a complete clean may not be possible. A further complication, in the case of some historic surfaces, is where there is erosion of the cement matrix at the surface, thus creating a roughened surface and increased porosity which could complicate the cleaning process, as well as leading to relatively rapid re-soiling. If staining has penetrated below the surface into the pores of the structure, it may not be possible to clean it without removing the near-surface layer of concrete and potentially exposing more porous material underneath to deterioration and decay.

Cleaning historic concrete, because of its innate porosity, is essentially similar to cleaning stone. The same risks apply. There is a wealth of research and advisory information available on the cleaning of historic masonry and the removal of graffiti that is also applicable to concrete. Historic Scotland has published comprehensive guidance on this topic: *Stonecleaning: A Guide for Practitioners* (1994)*; TAN 9: Stonecleaning of Granite Buildings (1997);* and *TAN 18: The Treatment of Graffiti on Historic Surfaces (1999).* As a general rule, it is best to start by using the least aggressive system and assessing the outcome before resorting, if at all, to stronger and potentially more damaging methods.

Before embarking on any cleaning exercise it is always advisable to undertake trial cleaning and the assessment of test panels, in an inconspicuous location, using the cleaning methods considered most appropriate. Specialist advice should be sought where there is potential to alter the character of historic concrete surfaces.

2.1.1 Cleaning methods

There are different ways to clean concrete surfaces. Choosing the most appropriate method requires consideration of the following: historic significance of the surface, extent of deterioration, and degree and nature of the soiling and staining. The three primary methods of cleaning concrete are water-based systems, abrasive systems and chemical systems (including poultices). There are numerous proprietary systems available, all of which are capable of inflicting permanent damage on the concrete surface. Use of these systems should only be undertaken by specialists with knowledge and experience of cleaning historic surfaces. It is not possible to review all of the available systems within this guide, but the main systems are outlined below.

The main cleaning systems are:

- **Low-pressure water**
- **High-pressure water**
- **Dry and wet-grit abrasive**
- **Chemical (including chemically impregnated poultices and films)**

Low-pressure water cleaning

Low-pressure water (mains pressure) is probably the least aggressive method of cleaning. However, it can be difficult with this method to remove stubborn stains that have penetrated the pores of the concrete. Water washing with non-ionic detergents can be more effective than using water alone. Steam cleaning is considered no more effective than water for removing staining or heavy soiling (Gaudette and Slaton, 2006). Sometimes washing with water to soften the deposit and brushing with non-ferrous brushes (to avoid iron staining) may be sufficient (Andrew *et al.*, 1994). Low-pressure washing followed by brushing may also be an effective precursor to chemical cleaning.

High-pressure water cleaning

High-pressure water can be used at a range of pressures up to 14,000kPa (c. 2,000psi). It is more aggressive than low-pressure systems, is generally damaging to historic concrete surfaces and is therefore not recommended.

Dry and wet-grit abrasive cleaning

A variety of abrasive cleaning systems are available. The two most common systems are dry and wet-grit blasting. Both are carried out at a range of pressures, using abrasive media of varying hardness. The more aggressive systems remove the soiling by eroding the surface, which can change the surface colour and texture, and lead to future deterioration. For cleaning vulnerable surfaces mechanical systems must use low pressure (c. 30 to 40psi) and minimally abrasive grit. A range of soft grits are available, including calcium carbonate, sodium bicarbonate, aluminium oxide, ground shells of walnut and coconut, and urethane sponge impregnated with tiny particles of plastic chip. Low-pressure micro-air-abrasive systems are available operating at pressures of typically 20 to 35kPa (3 to 5psi). They use very fine particles as the abrasive medium, such as aluminium oxide, calcium or magnesium carbonate powder and, under ideal conditions, are capable of removing soiling with little or no damage to the surface. Nevertheless, micro-air-abrasive cleaning can alter the surface texture and light reflection of smooth-finished concrete. Dry and wet-grit abrasive methods always carry the risk of creating a patchy appearance, especially on smooth surfaces.

Chemical cleaning

Chemical cleaning methods work by producing a chemical reaction between the cleaning agents, the soiling layer and the concrete. As concrete is a chemically reactive material, the cement matrix may be dissolved in the cleaning solution. It is essential to conduct trial cleaning in an inconspicuous location to ensure that the cleaning agents are suitable for use on the concrete. There are many proprietary chemical cleaning agents and methods available that can clean effectively but they may also alter the appearance of the concrete, for example by bleaching it, removing the surface layer or etching the aggregate (Gaudette and Slaton, 2006).

Chemical cleaning agents are either alkaline or acidic, and are available in varying degrees of concentration. Strong acids, such as hydrofluoric acid or hydrochloric acid, and alkalis should not be used. Concrete is readily attacked by most acids, the extent to which depends on the type of acid and its concentration. Acidic cleaners should not be used on acid-sensitive surfaces. However, the cement matrix of well-carbonated concrete may be less acid-sensitive, and low-concentration acidic cleaners may therefore be effective. Nevertheless

care is required as most commercial acidic cleaners are composed mainly of hydrofluoric acid, of varying concentrations, and often include some phosphoric acid to prevent rust-like stains developing after cleaning.

Alkaline cleaning agents, such as sodium hydroxide, tend to be used on heavily soiled surfaces as a degreasing agent before the application of acidic cleaning agents. The use of alkali alone, without neutralisation or extremely thorough washing, may result in the formation of potentially damaging salts in concrete, especially within any joints or cracks.

Poultices may be used to apply liquid chemicals in a controlled way to localised stains or specific areas. A poultice, which can be trowelled onto the surface, consists of an inert, absorbent material impregnated with cleaning chemicals. The poultice is then covered with plastic film and left in place for up to 24 hours before removal by scraping and washing. The removal process may be damaging to fragile surfaces if not carefully controlled. Care is required to ensure that one set of contaminants is not replaced by another.

More recently, 'clean-film' systems (sometimes referred to as latex poultices) using a range of specialist active chemical solutions bound into latex, have been used on sensitive surfaces with good results. The film is sprayed on and allowed to dry for a specified time, during which the solution reacts with, and binds to, the soiling substances. The latex film is then removed.

2.1.2 Summary of cleaning methods

A summary of cleaning methods is outlined in Table 1 below.

Cleaning method	Efficacy
Low-pressure water	*Not very effective on heavily soiled surface. Water steam cleaning is sometimes combined with brushing.*
High-pressure water	*Can be damaging. Not recommended.*
Dry-grit blasting: • *Low pressure micro-air-abrasive* • *Low pressure and soft grit* • *Medium – high pressure*	 *Recommended.* *Recommended.* *Not recommended.*
Wet-grit blasting	*Not recommended.*

Chemical
  Acid cleaners:
    • *Hydrochloric (muriatic) acid*
    • *Hydrofluoric acid*
 	
    • *Ammonium fluoride*
  Alkaline cleaners:
    • *Alkaline poultice*
    • *Latex film (clean film)*
    • *Caustic soda (sodium hydroxide NaOH)*
	
	To be avoided.
	To be avoided. Low-concentration commercial systems may be appropriate on non-acid sensitive surfaces.
	To be avoided. Risk of damage to siliceous materials/aggregate.
	
	Recommended. Scrape off and wash down after with low-pressure water.
	Recommended.
	To be avoided. Can leave dangerous salts in the pores.

Table 1. Overview of cleaning methods with general comments on their use on historic concrete (adapted from Amoroso and Fassina, 1983).

2.1.3 Specific stains and soiling

Rust stains

Rust stains should be carefully investigated and analysed to determine if they are due to reinforcement corrosion, which will require special treatment and repair, or some other sources, for example iron-rich aggregate or ferrous metal fittings attached to the concrete (Fig. 2). Proprietary cleaning chemicals suitable for rust stains typically contain oxalic or phosphoric acid solutions. Deep rust stains will require chemical surface treatments using a poultice, typically diatomaceous earth containing a dilute solution of sodium citrate with glycerol (CCAA, 2008).

Biological growth

Common biological growths on concrete include algae, bacteria, fungi, lichens and mosses. They will colonise surfaces wherever conditions of moisture, light, temperature and nutrients are suitable. Concrete is often covered by dark soiling, especially in zones of rainwater run-off, which may give the impression of being particulate in origin. However, it is more often the case that such soiling is biological which may then attract particulate deposition. Algae are probably the most ubiquitous of such growth and can range in colour from bright green to dark brown or black. In general, these growths, although considered by some as unsightly, are not directly damaging to the concrete. They can, however, indicate areas of concentrated water run-off which may be a concern and might need to be addressed before any cleaning is undertaken.

Removal of biological growth from surfaces can be difficult. Common advice, such as the application of chlorine bleach with pressure washing or vigorous scrubbing, is almost always inappropriate and can cause damage to historic concrete. The usual method of treating growths is through the controlled application of biocide washes. These are generally only effective in the short term and will require repeated applications at regular intervals to reduce the visual impact of the growths (Cameron *et al.*, 1997). To properly address such staining, repair or alteration of drip detailing may be required. Surfaces that have been roughened by aggressive cleaning methods will retain more moisture and may thereby encourage more prolific biological growth.

Fig. 2 Rust stains on poorly repaired historic concrete. The stains in this case may be due to the presence of ferrous metal underneath the repair.

The algal growth shown in Fig. 3 is caused by water run-off due to a defective sill detail. There is no evidence of water damage or biological deterioration to the render, and it is not responsible for the shrinkage crack.

Graffiti

Concrete surfaces can vary considerably in texture and permeability but most may be regarded as porous in relation to the penetration of graffiti-marking agents and solvents (Urquhart, 1999). A variety of graffiti types can be found. Those most frequently encountered are paint (several types) and felt-tip markers, either solvent-based (permanent) or water-based (non-permanent). The presence of surface features, such as pitting and cavities, further complicates the treatment process. In most cases, graffiti is viewed as unsightly, offensive, or both, and there is often pressure to remove it completely and as quickly as possible, by the most aggressive and cheapest method (Fig. 4). This typically involves high-pressure water or grit blasting, which damages the surface. Complete removal of graffiti which is absorbed into the surface, will be difficult to achieve without also removing the surface of the cement matrix. As with all cleaning methods, this should start with tests on a small area using the gentlest methods in the first instance. For historic concrete surfaces specialist advice should always be sought.

There are three main systems of graffiti removal:

- chemical (including proprietary systems)
- physical removal systems, which must be low pressure and use minimally abrasive grit (small-scale graffiti on vulnerable surfaces has been successfully removed using micro-air-abrasive systems)
- laser cleaning, which is suitable for museum quality, sculptural or particularly detailed work (essentially for small-scale graffiti as it is more costly than chemical or physical removal).

The removal of graffiti is covered in more detail in Historic Scotland's following publications: *TAN 18 – The Treatment of Graffiti on Historic Surfaces (1999)* and *Inform Guide: Graffiti and Its Safe Removal (2005).*

Oil and grease

These substances can quickly penetrate the concrete surface and are difficult to remove completely. Any surface grease should be gently scraped from the surface. Because of deep penetration, the most effective means of treatment is with a carefully designed poultice containing an alkaline degreaser.
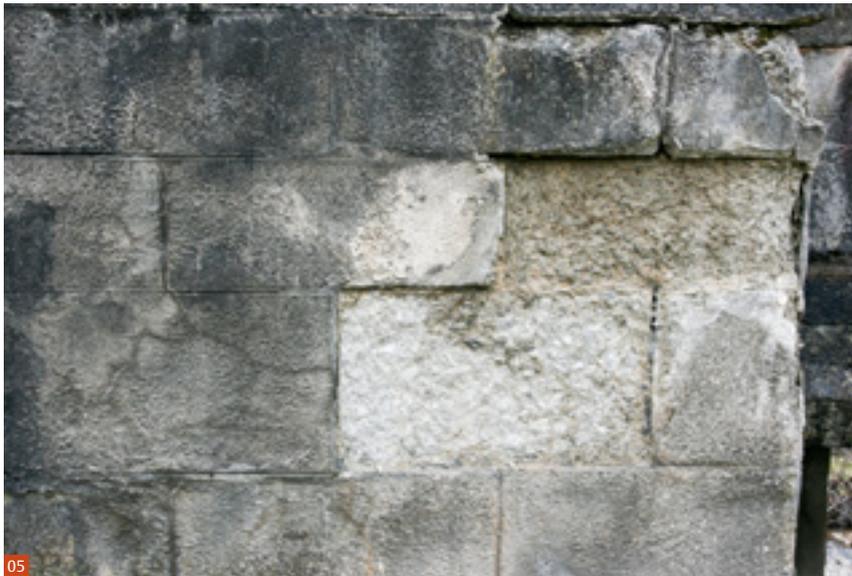
Fig. 3 The dark soiling is algal growth as a result of water run-off from a faulty sill and is unrelated to the shrinkage crack.

Fig. 4 Graffiti on historic concrete.

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Salts

Efflorescence (surface salts) and cryptoflorescence (salt crystallisation within the pores) are the hydration and crystallisation of soluble salts in the presence of moisture (Fig. 5). They will only cease when the sources of moisture and/or salt have been eliminated. Sulfate or chloride contamination may occur from within the concrete itself or from external sources, such as de-icing salts, marine aerosols, ground water, soils or cleaning chemicals applied to the surface.

In older concrete, efflorescence is more likely to be from sources other than the concrete, therefore elimination or reduction of external source(s) of water is the first step. It is important not to seal the concrete surface as this will encourage cryptoflorescence within the material. Light deposits of efflorescence can be dry-brushed from the surface. Heavier deposits may require scrubbing with water, high-pressure water washing (on sound surfaces) or treatment with a very dilute acid, such as phosphoric acid. When applying acid washes, surfaces should be thoroughly wetted before, and washed down after application to minimise suction and ensure the complete removal of any acid residues.

Cryptoflorescence occurs within the pores below the surface and is capable of causing detachment and loss of the surface in severe cases. As with efflorescence, elimination of the sources of moisture and salts must be the first step. Where contamination is not severe, brushing or washing may be sufficient. Where disintegration of the concrete has already occurred, the only practical solution is to cut back the decayed areas and patch repair with a compatible material. Sealing the surface with coatings that do not permit moisture or vapour transpiration can result in more rapid deterioration of the concrete. In the case where the concrete is heavily contaminated with salts it is likely that it will be impossible to remove the salts.

2.2 Surface protection

There are many surface protection systems available for concrete, especially modern proprietary systems. However, not all systems are appropriate for historic concrete structures as many treatments are irreversible should problems arise after application. Before any protection system is applied, it is recommended that laboratory and site tests are carried out to analyse existing coatings, to determine

the condition of the concrete surface and to detect the presence of any deleterious substances, such as chlorides or sulfates, that can affect the coating. It is important to establish compatibility of the coating with the existing concrete finish and its natural behaviour. Prior to a final decision on the selection and specification of a coating, it is essential to prepare trial samples to assess the suitability of the coating to ensure that there are no adverse effects to the concrete or its appearance. Examples of appropriate coatings might be a mineral paint matched to the original colour of the concrete.

2.2.1 Cement and lime renders

The normal practice in Scotland for early mass concrete walls, especially when used for the construction of domestic buildings, was the application of a protective or decorative render or harl coating, often with a painted or lime-wash finish. With the exception of a number of areas such as the Western Isles, in the case of most buildings constructed before the 1880s the coatings were likely to be lime mortar. After this date cement-based mortars became more prevalent and after 1920 were used predominantly. Early cements were produced on a relatively small scale, compared to today, and each manufacturer might have used individual 'recipes' giving the mortar somewhat different properties. However, with the passage of time, these early, lime-based coatings are now likely to have been replaced with cement-based systems. This should not be seen as a defect (as would be the case with traditional masonry) as cement-based materials are often compatible with early cement concretes. However some present-day cements are too hard for such applications.

Most historic concrete buildings in Scotland appear to have flat cement-based render coatings, many of which are generally in good condition, except where cracking has taken place, usually as a result of shrinkage or embedded metal corrosion. Fig. 6 shows a cement render finish to early no-fines concrete. The rough texture and porous nature of this concrete substrate provides an excellent bond for the render. In this case, the thickness of the render is less than 10mm.

Render should be physically and chemically compatible with the substrate. In the case of historic concrete both lime and cement mortars are compatible with either lime or cement-based binders in the concrete. Also, dense concrete does not have the same degree of porosity as that of sedimentary stones (e.g. sandstone) or lime mortar and, while a degree of permeability is important, this is less critical than with traditional masonry. Provided that the existing render is in sound condition, a patch repair with a lime-mortar or cement-mortar render should provide satisfactory results.

If it becomes necessary to replace a render finish to historic concrete then research is required to try to identify the material, mix, colour and texture of the original and, as far as possible, to replicate this in the new coating while preserving architectural features.

2.2.2 Alteration of/to building detailing

Additional protection of historic concrete surfaces may also be achieved by the addition of flashings, drips or other water control devices which redirect and/or shed rainwater. This is particularly crucial at roof and wall junctions and along parapets, where water-related deterioration and decay is often caused by poor detailing and inadequate protection from run-off. Alteration of original features should be carefully considered in terms of their effect on the appearance of a structure, and appropriate permissions, such as Listed Building Consent, are likely to be required if a structure is listed.

Fig. 6 Cement render coating applied to a no-fines concrete (c. 1880).
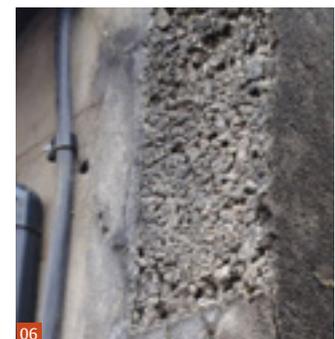
3. Repair methods and materials

In common with all conservation repair work the selection of the most appropriate repair system is not always straightforward and can range from a 'do nothing' approach to a full-scale rebuild. It is important to understand the range and types of repair techniques that are available and their impact on the character of the structure. The repair of historic concrete requires a level of skill comparable with that required for masonry conservation repair.

Key factors that should be considered prior to conservation repair:

- **Importance or significance of the structure**
- **Impact of the repair on the character of the building or structure**
- **Urgency and severity of the deterioration**
- **Appropriateness and practicality of the repair option, and assessment of the repair systems available for the particular situation**
- **Projected life of the structure**
- **Projected life of possible repair options and methods**
- **Finance available and whether total funding is obtainable immediately or in instalments**
- **Consequences of delayed or phased repair**
- **Relevance of previous repairs or modifications**

Deterioration can reach the stage when repair becomes unviable and the building element has to be replaced. This should be considered as a last resort for major elements but, for small precast units, it may be more economical to cast a replica. Such an approach can be advantageous for small ornamental features when a number of units can be cast from the same mould, which can then be kept for future repairs. However, as with other repairs, attention should be paid to careful matching with the existing concrete, to the extent of ensuring that imperfections in the original castings are included in the replacements. The replacement should replicate the original, including mix design, surface finish, texture, compressive strength and porosity so that it will weather in a compatible manner with the original.

If the structure is beyond repair, it may be demolished (with consent from the local authority and/or Historic Scotland). In this extreme case, prior to demolition, the building should be fully recorded, including all the available original design, construction information and material specification and a full set of 'as built' drawings and photographs prepared.

3.1 Surface preparation for repairs

Surface preparation is a vital part of the repair process. Inevitably some original material will be removed, and this removal should be carefully undertaken. Cutting out to existing joint lines or board marks will help with matching the repair to the original finish. Cuts should not have feather edges; a slight dovetailed or under-cut profile is to be preferred. Straight and smooth saw-cuts should be avoided because a smooth surface reduces bond and a straight edge may be too severe a delineation between the concrete and the repair. The key points for surface preparation are:

- No unnecessary removal of historic material.

- Remove loose and crumbling material to expose the full extent of the defect.

- Area of repair should only extend beyond deteriorated concrete as is necessary to achieve a sound surface onto which the repair can firmly adhere.

- Exposed edges of the repair should be roughened by hand tools to better conceal the junction between the existing concrete and the repair.

- The depth of the repair should extend a minimum of 20mm beyond any reinforcement or should at least be equal to aggregate size.

- Existing concrete exposed within the area of repair should be sound, contain no cracks and be free from loose material and contamination such as oil and grease.

- The exposed repair area and reinforcement should be carefully cleaned out with wire brushing, compressed air or sandblasting as appropriate, and any loose debris completely removed from the prepared area. Protection should be provided to the surrounding surfaces prior to cleaning.

- Apply proprietary primer to protect the concrete and steel reinforcement after cleaning.

- Surfaces treated with sealants or other films which retard the adhesion and curing of the repair material must be removed.

3.2 Repair materials and mixes

Because every historic concrete structure is unique there can be no prescribed specification for repair materials and mixes to be used. The lack of a unified Code of Practice (technical standard) at the time of construction, variations in mixes and binders, and the use of local sources for aggregates mean that there can be considerable variations in the properties of early concretes, and this needs to be fully considered when specifying repair materials. Even within a specific structure there may be differences in the concrete between adjacent areas, for example due to differences in mix proportions and in the compaction and curing during construction which can affect porosity, density and strength, thereby influencing the approach to repairs.

There may be problems associated with the function or location of the structure which can influence the repair strategy. It may be necessary for the repair to achieve an early gain in strength because of restricted working conditions due to weather or aggressive ambient environment, or to bring a critical element quickly back into use. A change in use of the structure may indicate that the repair is required to provide additional chemical or abrasion resistance. These factors may mean that in particular circumstances like-for-like repair using cementitious materials without modification may not be the best approach.

As a general rule, however, the replacement concrete should be compatible with the existing concrete in terms of strength, permeability, elasticity and movement. It should have the same characteristics as the substrate, and cement-based mixes are preferred to polymer-based repair materials. Selection of the repair materials and mixes for historic concrete requires specialist knowledge and experience.

> **Key considerations associated with the selection of repair systems:**
> * Sourcing and matching repair aggregates
> * Shrinkage of repair – cementitious mortars exhibit greater shrinkage than that of concrete
> * Colour matching
> * Inadequate quality control
> * Bond to substrate
> * Use of admixtures

Sourcing and matching repair aggregates

Sourcing matching aggregates for size, grading, colour, shape and rock type can present difficulties. The original concrete may have used shingle and sand from the sea shore, and it will be inappropriate to use a similar source because of the likely salt contamination and poor grading characteristics. It may not be possible to identify the source of the original aggregate, or it may no longer be available, and time may be required to identify an alternative source.

Shrinkage of repair

The use of modern (present-day) cement and repair mortars can cause issues relating to the strength and shrinkage of the modern material relative to the original, as the modern material is likely to be stronger. Shrinkage stresses can either produce cracks between old and new or cause disruption to the old concrete at the interface. Cementitious repair mortars generally exhibit increased drying shrinkage compared to concrete because of their higher water volume, higher unit cement content and higher cement-paste-aggregate volume (American Concrete Institute Report 1996, reapproved 2001). The use of these mortars must be carefully considered and controlled.

Colour matching

It can be difficult to obtain a good colour match with modern cements and cementitious repair mortars. White or general-purpose cement mixed with a non-hydraulic lime, combined with a good choice of aggregates, may assist with colour matching.

Inadequate quality control

In general, the volume or area of concrete to be repaired is likely to be small relative to the mass of the original concrete. While mixing repair mortars or concrete on site is possible and was the norm until quite recently, the issue of quality control needs to be considered when small-scale work is being undertaken. For small patch repairs it is now common to use proprietary repair mortars which have the advantage of being quality controlled products, but suffer from the disadvantage that they will be unlikely to match the variations in the concrete which may occur throughout the structure. It is difficult to obtain a near-perfect match between the original concrete and the repair mortar, which is

often modified with polymers to impart particular properties, such as improved durability, frost resistance and reduced shrinkage. The suitability of a proprietary repair mortar for a specific situation should be carefully assessed and is likely to involve test applications in inconspicuous areas.

Care should be taken to ensure that any admixtures or additives (air-entrainers, expanders, retarders etc.) which can impart advantages to the repair medium, do not reduce the pH of the concrete or introduce excessive amounts of air (Reed *et al.*, 2008).

Bond to existing concrete

Achieving a satisfactory bond between the repair and the original concrete can sometimes be difficult. A cement-slurry coating to the faces of the exposed concrete in the repair area may be sufficient to improve the bond with the repair. While a number of proprietary bonding agents are available, caution is advised as polyvinyl acetate agents may lower the pH of the concrete (Reed *et al.*, 2008). Some agents are unsuitable in damp conditions and break down, and others can form barriers that restrict moisture transfer within the material.

Use of admixtures

Where the concrete decay is due to an aggressive environment, conventional concrete without admixtures should not be used for repair unless the aggressive environment that caused the original problem has been eliminated. A reduced service life for the repair may have to be accepted if this is not possible.

3.3 Concrete patch repairs

3.3.1 Patch repair methodology

Patch repair is a common form of repair to concrete and is employed to deal with localised surface deterioration due to spalling and crazing, e.g. as a result of reinforcement corrosion and defects exacerbated by freeze-thaw cycles (Fig. 7). A typical procedure for patch repair to reinforced concrete involving the removal

Fig. 7 Concrete deterioration as a result of water penetration through shrinkage cracks with subsequent freeze-thaw cycles causing surface disruption. A patch repair would be suitable in this case.
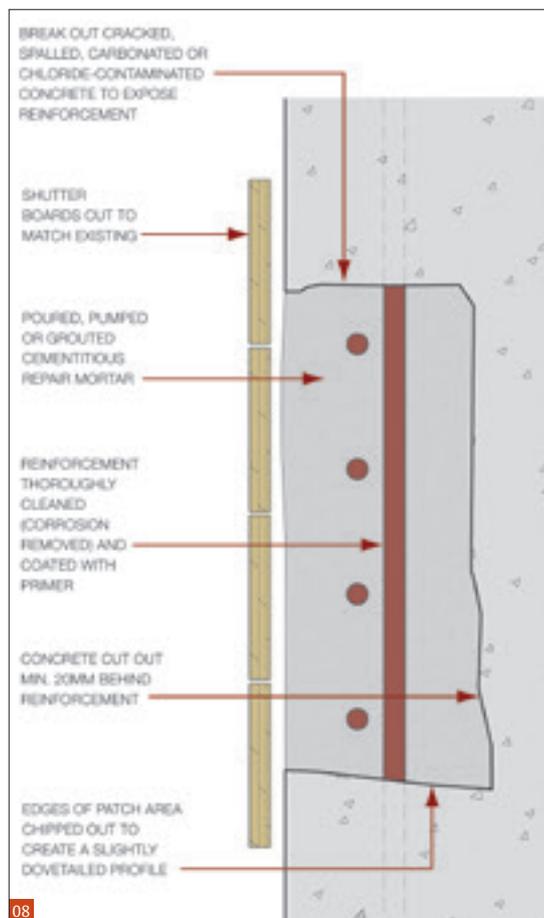
and replacement of concrete is illustrated in Fig. 8. Insufficiently detailed patch repairs can result in a poor appearance and continued decay (Fig. 9). Structural implications should be considered before carrying out any patch repairs.

The primary considerations when executing a patch repair are as follows:

- Replace like-for-like, therefore lime or cement-based binders (as appropriate) should be used in preference to modern (present-day), non-cement repair materials.

- If a complete section of a reinforced concrete element is removed, ensure that adequate temporary support is provided before cutting out concrete and/or steel.

- Badly corroded reinforcement may need to be replaced by splicing in new steel. Use of galvanised steel should be avoided as this may promote bi-metallic corrosion with mild steel.

- The finished repair should match the existing concrete as closely as possible with respect to its visual appearance and physical properties such as compressive strength, permeability, mix proportions, aggregate types and grading (Fig. 10).

- Trial mixes should to be prepared to assess the match with the existing concrete. The repair concrete is unlikely to match exactly the colour and texture of the weathered surface of the existing concrete, and the repair will change as it ages and weathers. Repair mortars may sometimes be modified with additives to enhance durability and to reduce shrinkage in order to control subsequent cracking.

Fig. 8 Typical procedure for patch repair to reinforced concrete.

Fig. 9 Poorly executed patch repair to a historic concrete structure. Note the evidence of previous unsuccessful repair.

Fig. 10 Replacement precast concrete blocks to the parapet of this 1935 bridge, cast to profiles to match the existing (Category B-listed).

- Trials should also be conducted with different types of formwork and finishing to obtain the best match with the original finish. Trial panels should be viewed when both wet and dry.

- Formwork is preferred to trowel finish as this permits proper mix proportions and better consolidation. Replicating original formwork will give a better visual appearance to the repair (Fig. 11). A parge coating, i.e. a thin coat of mortar, is not recommended unless required to match the original finish (Gaudette and Slaton, 2006).

- For a large, shallow surface area, spray-applied concrete may be appropriate.

- In the case of a deep patch, or where there is inadequate concrete cover, new stainless steel or phosphor bronze armatures, or pins, may be required to hold the repair in place.

- Rapid curing of the repair will lead to shrinkage and surface cracking at the junction with the existing concrete and sometimes within the surface of the repair. Adequate curing techniques that allow sufficient setting time should be used.

- The patch repair of historic concrete is distinct from work with new-build concrete, and a high degree of experience, skill and craftsmanship is required to achieve a finish that matches the sometimes variable finish of historic concrete.

3.3.2 Common patch repair problems

When the considerations for patch repairs identified above are considered against the evidence, a number of observations can be made regarding the effectiveness of the repair within a conservation context.

Patch repair with movement joint

Patch repair with a movement joint is not a simple, straightforward operation. It requires careful analysis of the existing concrete including mix proportions, aggregate, porosity, surface finish and texture and often benefits from a petrographic analysis of samples of the original concrete to determine its appropriate chemical composition. The execution of the patch repair in Fig. 12 is quite crude and, while an attempt has been made to match the original profiles (Fig. 13), little attempt has been made to replicate the surface finish and texture of the existing concrete. The original concrete has been cast *in situ* using formwork (boards) to produce the finish while the surface of the repair gives the impression of being cement-rich and 'over-worked'. The 'joint' or junction between two lifts of the vertical flutes does not occur on the existing material and will be a source of moisture penetration in future, possibly leading to premature failure of the repair. The cement paste smeared over existing surfaces, possibly to cover a small patch, is unsightly.

Fig. 11 Recent patch repair to historic mass concrete using formwork (shuttering) © Rowan Technologies Ltd.

Fig. 12 Recent repairs to a c. 1935 structure (Category B- listed).

Fig. 13 The original finish and profile of the cast concrete shown in Fig. 12.

Repair to no-fines concrete sill

The repair to a no-fines concrete sill shown in Fig. 14 was part of this listed building's refurbishment about 25 years previously when, rather than replacing deteriorated concrete with like-for-like, a softwood insert was used, covered with expanded metal lath and cement render, and finished with a textured paint to match the rest of the building. The subsequent corrosion of the expanded metal has disrupted the render.

Repair to early reinforced concrete frame

A recent surface repair to an early concrete frame appears to be superficial but it may prove to be problematic (Fig. 15). Surface cracks are already observable, which are allowing water penetration of the concrete.

3.4 Repairs of cracks in concrete

3.4.1 Causes of cracks

As discussed in Part 2 of this series of short guides on historic concrete, cracks are ubiquitous in concrete and may or may not be significant. Cracking can be the result of one or more factors, for example drying shrinkage, thermal contraction and expansion, restraint to shortening (the effects of localised restraint), corrosion of reinforcement, expansive salt action, structural settlement and applied loads. With the exception of cracking resulting from reinforcement corrosion most cracks in historic concrete are unlikely to be recent, unless there has been a change in external conditions such as support, ambient environment or loading. A summary of the causes of cracks is outlined in Table 2 below. If cracking is due to drying shrinkage, it is likely that the cracks will have stabilised. However, other issues, such as freeze-thaw action or reinforcement corrosion, may now have commenced as a result. An example of a shrinkage crack is shown in Fig. 16.

Chimneys tend to have a limited thickness of concrete surrounding the flue and sometimes, if not lined when constructed, this can result in parallel cracking in the gable wall (Fig. 17). Early concrete chimneys are particularly vulnerable to cracking due to sulphur-bearing flue gases escaping through cracks or weaknesses in the chimney lining and thereby penetrating the concrete structure (Fig. 18). Sulfates can penetrate the concrete resulting in the formation of expansive salts, leading in turn to the formation of predominantly horizontal cracks especially at junctions between concrete lifts. A summary of the causes of cracks is outlined in Table 2, and is discussed in more detail in Part 2 of this series of short guides on historic concrete.

Fig. 16 Shrinkage crack in the abutment of a 1930s reinforced concrete bridge. Note that the crack may now be increasing over time due to freeze-thaw action.

Fig. 17 Parallel cracks in a mass concrete gable wall, following the line of a flue. The flue may not have been lined when constructed, and the concrete has reduced thickness at the external flue wall.

Fig. 18 The concrete chimney shows typical evidence of cracking as a result of sulfate salts formed from flue gases. The staining also indicates the lack of a formed drip on the cope.

Source	Causes	Comments
Drying shrinkage	*Loss of moisture from cement paste combined with inadequate movement joints and/or reinforcement*	*Cracking is the result of the combination of shrinkage and restraint (usually provided by another part of the structure). There may be a noted differential between the shrinkage of concrete with sandstone aggregate and concrete with granite aggregate.*
Tensile stresses	*Pressure exerted on concrete due to tension*	*Concrete works well in compression but not in tension. Under tension it will tend to crack, resulting in fine tension cracks (minor) or more serious structural cracking if excessive.*
Thermal stresses	*Temperature differences within the concrete structure due to heating and cooling*	*Cracking in mass concrete (especially in large volume concrete structures) can be caused by heat liberated during cement hydration or more rapid cooling of the external surface. Results in tensile stress on the exterior which may cause cracking.*
Chemical reaction	*Alkali-silica reaction*	*Results in the formation of a swelling gel causing local expansion and may result in the complete deterioration of the concrete. Cracking characterised by a fine network of cracks (star or 'Isle of Man' cracks).*
	Sulfates	*From sulfate-bearing ground water, flue gases or from the atmosphere. They crystallise as salts within the pores and disrupt the concrete. Cracking is closely spaced.*
	Chlorides	*Water-soluble calcium chloride from de-icing salts in particular can be very damaging to concrete, mainly to reinforced concrete due to accelerated corrosion of the steel.* *Very little can be done to repair concrete that has been subjected to these forms of chemical attack.*
Weathering	*Freeze-thaw cycling wetting and drying*	*Cracking due to natural weathering is usually conspicuous. Damage by freeze-thaw is the most common weathering phenomenon and is due to pressure exerted by ice crystals within the pores. Cracking may appear serious but is usually a surface effect and may not have progressed to depth.*
Corrosion of reinforcement	*Exposure of reinforcement due to carbonation*	*Alkalinity of the concrete is reduced through carbonation and therefore corrosion protection is reduced.*
	Aggressive ions (chlorides)	*Chlorides ions can increase the rate of corrosion. Corrosion cracks form along the bar (i.e. parallel to the reinforcement), cause spalling or delamination. As cracks form a pathway for oxygen, moisture and chlorides, minor splitting cracks can result in severe corrosion.*
Inappropriate design	*Early concrete designers' and builders' lack of understanding of concrete and reinforcement design*	*Typical errors may include: Lack of (or poor positioning of) movement joints or contraction joints; Concentration of stresses at re-entrant corners, especially at windows and doors, resulting in cracking at such junctions; Inadequate reinforcement; Restrained creep; Improper foundation design; Inadequate drainage to remove surface water.*

Table 2. Summary of main causes of cracks in historic concrete structures (based on ACI 224 Report, 2007).

3.4.2 Treatment of cracks

Concrete is strong in compression but weak in tension and as a result cracking, to some degree, is a common and expected occurrence. Before a decision is made to repair a crack, it is important to determine its cause, whether the crack is *active* or *dormant* and whether or not reinforcement corrosion is present. It is natural for concrete to crack. If cracking is due to reinforcement corrosion or has been responsible for the corrosion, it is essential to repair the cracks and treat the corrosion, otherwise corrosion will continue and disrupt the repair. A dormant crack, if narrow, can be more easily dealt with than an active crack and the repair will take a different form. However, even a dormant crack can allow water penetration and encourage biological growths within the crack which, combined with freeze-thaw cycles, can gradually erode the surrounding concrete. An active crack is more serious and requires the cause(s) of the movement to be identified before a repair should be executed.

When dealing with cracks in mass concrete walls it is important not to view a crack in isolation but to assess the overall pattern of cracks in the building (*see* Part 2 of this series of short guides on historic concrete). While an individual crack may not be structurally significant, a series of parallel cracks (either vertical or horizontal) may significantly weaken a wall. The wall may then cease to act as a complete structural unit but becomes a series of isolated panels upon which loads from roofs, floors and beams become concentrated with the cracks preventing the transfer of loads over the whole area of the wall. In scenarios such as this, a structural assessment carried out by a structural engineer is required.

As there are many systems for crack repair, both by traditional and specialist proprietary methods, it is recommended that a careful examination is carried out to determine the extent and cause of the cracking. The selected repair procedure will depend upon the particular objectives to be achieved.

Objectives of a crack repair:

- **Restore or increase strength**
- **Restore or increase stiffness**
- **Improve functional performance**
- **Provide water tightness**
- **Improve appearance of, and/or match, concrete surface**
- **Improve durability**
- **Prevent development of a corrosive environment at reinforcement**

It is almost impossible to completely disguise a crack repair. It may, in fact, become even more apparent. Examples are mass concrete walls in domestic buildings which are often painted and contain shrinkage cracks which are relatively narrow. Caution must be exercised in the choice of method; for example, repairs such as epoxy injection, and routing and sealing will be very difficult to disguise. If the cracks are long-standing, dormant, of narrow width, and there are no water penetration problems, they may be best left untreated. Depending on the context of the historic surface, some form of coating over the entire surface may be required.

The main crack repair methods are summarised below. It should be noted that the methods identified below do not include structural strengthening of cracks using steel reinforcement or polymer impregnation.

Epoxy injection

Epoxy injection is typically used for dry cracks only. It can fill cracks as narrow as 0.05mm. Entry and venting ports should be provided at close intervals along the crack, which should be sealed on exposed surfaces. The epoxy should be injected under pressure. Care is required when injecting cracks that are not visible on all surfaces as uncontrolled injection can cause damage. Epoxy leaves a glossy appearance. If high injection pressure is not required, a removable, strippable plastic surface sealer can be applied along the surface of the crack and removed after the injection to leave a gloss-free surface. This type of repair requires a high degree of skill to achieve satisfactory execution.

Routing and sealing

Routing and sealing can be used to treat narrow and wide cracks where structural repair is not necessary. It is most suitable for flat horizontal surface cracking. The crack is widened by cutting a vertical groove of approximately 6 to 25mm depth along the surface of the crack (routing); then a sealant is placed into the clean, dry groove (Fig. 19). Typical sealants include epoxies, urethanes, silicones, polysulfides, asphaltic materials or polymer mortars. Cement grouts in this type of application should be avoided as they can have a tendency to cause further cracking. Active cracks should be repaired using a bond breaker at the base of the routed channel and a flexible sealant then placed in the channel (Fig. 20). The width of the channel is usually at least twice the depth, which permits the sealant to respond to movement of the crack. This method is quite simple compared to epoxy injection.
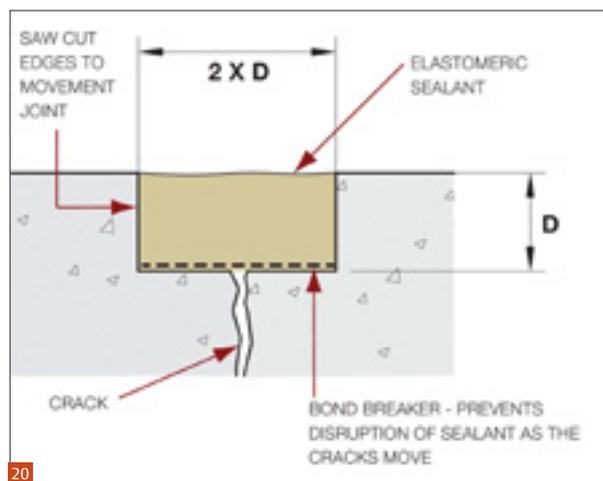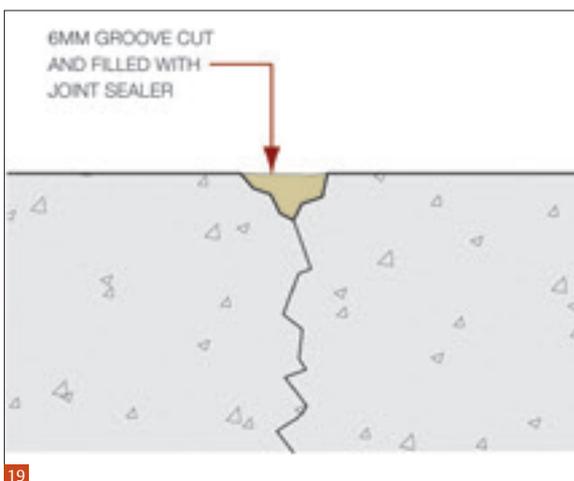

Fig. 19 Repair of cracks by routing and sealing.

Fig. 20 Repair of active crack with bond breaker.

This method is only applicable when the crack runs reasonably straight and is accessible at one end, i.e. along the depth of the crack, for instance in the case of a vertical crack in a retaining wall, which is accessible from the top. A 50-70mm diameter hole, centred on the crack, is drilled and should be large enough to intersect the crack along its full length. The hole is cleaned and filled with grout to provide a key to prevent transverse movement of the adjacent concrete sections.

Cement grouting

Cement grouting is typically applied to wide cracks in thick concrete walls. It is effective for stopping water leaks but not for structural bonding of the cracked sections. The crack is cleaned and sealed grout nipples (seats) installed at intervals along the crack to provide a connection with the injection apparatus. The crack should be sealed between the nipples with cement paint, sealant or grout, and the seal should then be tested. The crack is grouted in sections, starting at the lowest nipple and injecting until the grout level reaches the nipple above. For narrow cracks a cement and water mix is used, for wider cracks cement plus sand and water may be required. It is important to use as low a water-cement ratio as possible to maximise strength and reduce shrinkage.

Chemical grouting

Chemical grouting is primarily used for sealing cracks from water penetration (Fig. 21), as narrow as 0.05mm. Low bond strengths mean that this is not suitable for structural repairs. Typical materials are urethanes and acrylamides, activated by water or catalyst to form either a gel, a solid precipitate or a foam that fills the void space within the concrete. It is suitable for use in moist environments. This type of repair requires a high degree of skill for satisfactory execution.

Dry packing

The hand placement of low water-cement content mortar, tamped or rammed in place, can be used to fill narrow slots cut from dormant cracks, but is not advisable for use on active cracks. The low level of shrinkage in the mortar, coupled with a tight fit, provides durability, strength and water tightness. The crack should be

Fig. 21 Chemical grouting of cracks in a reinforced concrete bridge. Note the indication that moisture is still present within the concrete.

cut to provide a slot about 25mm wide and 25mm deep, undercut at the base so that the base width is slightly wider than the surface width. The slot is cleaned and dried, and a cement-slurry bonding coat, i.e. cement and fine sand paste, or appropriate latex bonding compound is applied. Then a dry pack mortar is applied immediately which consists of one part cement to three parts suitable sand plus just enough water so that the mortar will stick together when moulded into a ball. The mortar should stand for around 30 minutes before placing to allow for shrinkage. Each layer should be compacted in 10mm thicknesses, the surface scratched before application of the next layer. In order to provide a colour match with surrounding concrete, ordinary cement may be blended with white cement if appropriate.

Autogenous healing

This process is best suited to fresh crack situations and may not be effective for long-established cracks in historic concrete. It is a natural process for repairs to narrow-width, dormant concrete cracks in the presence of moisture and the absence of tensile stress. It has a practical application for closing dormant cracks in moist environments such as mass concrete and water-retaining structures. Typically, cracks up to 0.2mm width will autogenously seal within 28 days; cracks up to 0.1mm will seal within 14 days. Healing occurs by the formation of calcium carbonate within the crack, formed by exposure to carbon dioxide and water, which fills the void space and also bonds crack surfaces and restores strength to the concrete. Saturation of the crack and adjacent surfaces with water during the healing process is essential; submergence is desirable and should continue for the entire healing process.

3.5 Treatment of reinforcement/embedded ferrous metal corrosion

3.5.1 Causes of corrosion

Corrosion of reinforcement or other embedded ferrous metal in concrete is one of the principal reasons for the deterioration of reinforced historic concrete. As the concrete ages, under certain conditions the corrosion of steel reinforcement becomes more advanced. It is thus a time-dependent process.

Corrosion of reinforcement is a well-understood electrochemical process. More detailed information is available in publications such as *The Repair of Reinforced Concrete* (Broomfield, 1996). Such corrosion is the result of three main causes: water penetration, chloride attack and corrosion exacerbated by carbonation.

Water penetration

In Scotland, there is a particular problem of corrosion of wrought iron or steel lintels over openings likely to be caused by direct water penetration through cracks, water percolation through no-fines concrete or surface condensation (Fig. 22). It is difficult to identify sound steel from wrought iron by visual inspection alone. However, the forms of corrosion are different. Wrought iron, when badly corroded, delaminates at the edges, while steel rusts on the surface and does not delaminate.

Fig. 22 Disruption to concrete from corroding and delaminating wrought iron lintel (c. 1870s).

Chloride attack

Chloride ions present in de-icing salt and marine environments are highly mobile and, when in solution, can penetrate through pores and cracks into concrete. When these come into contact with steel reinforcement, or other ferrous metal, the steel oxidises to form corrosion products that can have a volume of up to ten times that of the original metal. Only a small increase in the volume of the corroded steel may be sufficient to cause cracking of the concrete (often called 'oxide jacking' or 'rust jacking'), leading to further deterioration.

Corrosion exacerbated by carbonation

Carbonation is the general loss of a stable, passive (unreactive) alkaline composition by neutralisation of the concrete, from reaction with atmospheric carbon dioxide. This alkalinity provides 'passive protection' to embedded reinforcement. The carbonation process moves as a 'front' through the concrete over time and thus, once it reaches the reinforcement zone this 'protection' is removed and the reinforcement is no longer protected from corrosion risk. In the case of a corroded lintel, such as illustrated in Fig. 22, the repair should follow this procedure:

- It may prove necessary to support the wall and other structures above the lintel. This may require the use of needles (punch holes through the wall above the lintel at regular intervals and insert temporary beams which are propped up).

- Carefully cut out and repair the damaged concrete around the lintel – only the minimum necessary to accommodate the replacement lintel – and remove the corroded lintel.

- Insert reinforced precast concrete lintels of a similar size.

- Insert slate wedges and dry pack between the top of the lintel and the underside of the original concrete.

- Repair concrete and reinstate the cement render and other finishes, carefully matched with the existing material. Analysis of the original materials may be required to ensure an appropriate mix specification.

3.5.2 Removal of affected concrete and steel

In the treatment of cracks, removal and replacement of the affected area may seem to be the simplest approach. However there are several issues which should be considered (Broomfield, 1996) and these are summarised below:

- Cutting out may not remove all the areas that are affected, particularly areas which do not exhibit evidence of decay at the surface.

- Repairs can lead to an acceleration of corrosion in adjacent steel.

- The repairs may be difficult to match with the existing concrete (*see* also section 3.5.3).

- Removal of a large area of concrete will require a temporary and expensive support to be in place.

For small reinforced precast units, it may not be feasible to cut out and remove the affected areas or use electrochemical treatment methods (*see* section 3.5.4). Complete replacement of the unit with a carefully matched replacement may be the most successful approach. In conservation terms, this could be considered to be similar to the replacement of a decayed stone in a masonry building. The cutting out and removal of portions of reinforcement, if required, should only be directed by a structural engineer and is not covered in this guide.

3.5.3 Protective coatings

Protective coatings and sealers, designed to reduce moisture and chloride penetration, can be helpful when chloride ion concentrations at the level of the reinforcement are within the acceptable limit, or if the depth of carbonation is less than the cover to the reinforcement. However, these are ineffective and do not address latent damage if corrosion has already started and direct water impingement has not been addressed (Broomfield, 1996). While coatings and sealants are colourless and may not be too obvious, they do tend to leave a noticeable surface sheen. In the case of historic reinforced concrete, careful assessment of the particular condition and circumstances is necessary before this approach is adopted.

3.5.4 Electrochemical treatments

There are several electrochemical processes available for the protection of steel reinforcement, which work by mitigating the corrosion process. These systems cannot repair reinforcement that has already corroded but can restrict corrosion damage to those areas. The principle is that when two dissimilar metals are coupled together in an electrolyte (in this case, the concrete), the metal with the higher potential for corrosion (usually zinc) will corrode in preference to the more noble metal (reinforcing steel). All such systems have to be carefully designed because they can cause damage to the concrete. Some systems include embedding a sacrificial anode below the surface of the concrete. Not every system will be effective on all types of structures. Nevertheless, electrochemical systems can be less disruptive to the concrete surface than patch repair and can reduce the need for major repair schemes.

There are three main electrochemical systems: cathodic protection, electrochemical chloride extraction and re-alkalisation. While both cathodic protection and chloride extraction have been shown to extend the service life of treated structures, electrochemical chloride extraction may reduce the need for regular maintenance.

Cathodic protection

This system has been employed successfully for many years, and is used mainly against chloride attack. There are two forms of cathodic protection.

1) The *sacrificial anode (passive) system* is where an auxiliary anode is connected to reinforcement so that the entire reinforcement becomes a cathode. The anode is formed from a less noble metal, such as zinc (though more recently conductive paint or a titanium mesh placed permanently on the face of the concrete has been used as the anode; the latter systems may, however, not be acceptable on a historic concrete surface). The sacrificial anode corrodes and is replaced at the end of its design life (between five and twenty years depending on the particular circumstances and the system used). This can be a low-cost solution for corrosion mitigation of chloride-contaminated and carbonated structures. It is particularly suitable for patch repairs as it provides protection at the interface between the repair and the remaining carbonated concrete when the sacrificial anode is positioned near the edge of the patch.

2) The *impressed-current cathodic protection system* is the most effective means of mitigating steel corrosion but is costly to install, is a permanent feature and requires continuing monitoring and maintenance. There are a number of proprietary systems available which typically work by distributing sufficient electrical current from a direct current supply to overcome continued corrosion in the structure. In some systems, small-diameter anodes are inserted into pre-drilled holes not more than 600mm apart, and a saw cut, approximately 10mm deep and 8mm wide, is made into the concrete between the holes. The anodes are then connected by a titanium wire grouted into the slots. It is difficult to install such a system without damaging the surface of the historic concrete. The system was used to protect the heavily chloride-contaminated bottom section of the main supporting beams during the refurbishment of the Bervie Jubilee Bridge, Aberdeenshire (Fig. 23) where over 8,500 discrete anodes were installed and connected to a remote monitoring system.

Where cathodic protection systems are to be employed it is important to recognise that remedial repairs carried out in conjunction with cathodic protection must be compatible with the system used. Effective operation and maintenance are essential for continuous service. If systems are not routinely and properly monitored, problems may develop that leave the reinforcing steel unprotected (ELTECH Research Corporation, 1993).

Fig. 23 Reinforced concrete Bervie Jubilee Bridge, Aberdeenshire, built 1935. Impressed-current cathode protection system used to protect the bottom section of the main supporting beams.
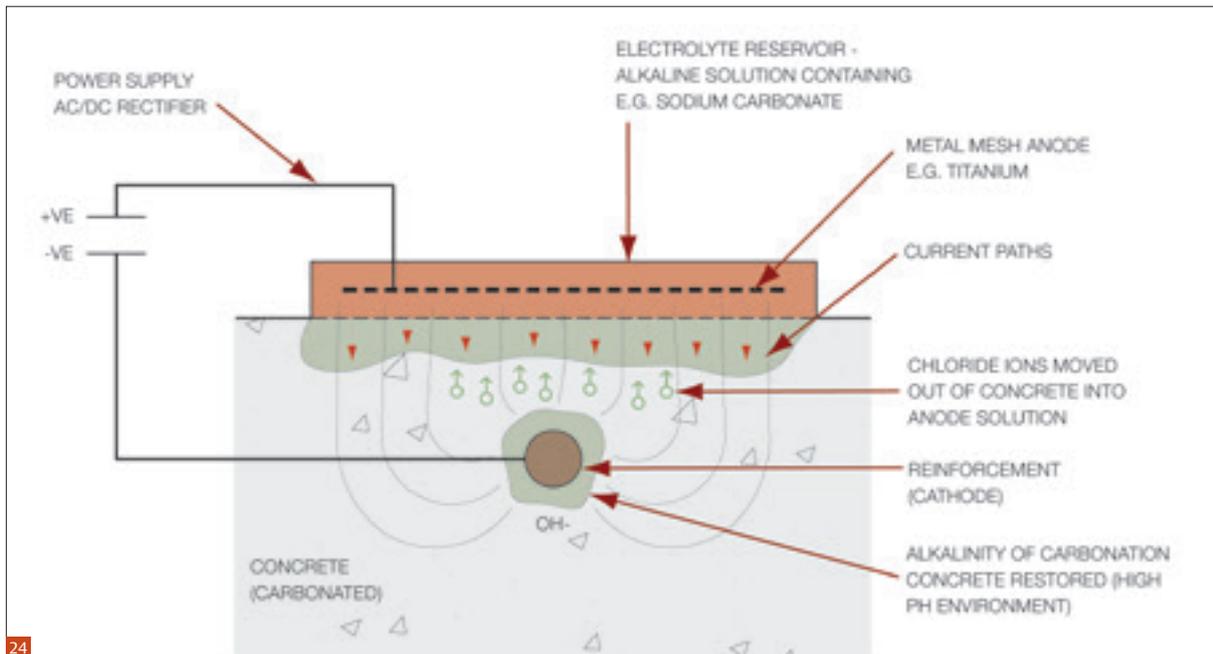
Fig. 24 Diagram illustrating chloride
extraction and re-alkalisation processes.

Electrochemical chloride extraction

Electrochemical chloride extraction is a form of desalination and is a 'once only'
process which extracts chloride ions from contaminated concrete and reinstates
the passivity of steel reinforcement. Chloride extraction is carried out temporarily
by applying an electric field, from a DC source, between the reinforcement in the
concrete and an externally mounted titanium anode mesh (the surface anode
is typically in place for a few weeks). During the process, the chloride ions are
repelled out of the concrete away from the reinforcing steel towards the external
anode. Fig. 24 illustrates both chloride extraction and re-alkalisation. At the same
time, electrolysis at the reinforcement surface produces a high pH environment
and returns the environment surrounding the steel to a passive condition. Where
there is a danger of further chloride ingress, a chloride-resistant coating may be
required.

Re-alkalisation

Re-alkalisation is a similar process to chloride extraction and is used in carbonated
concrete to restore the pH to its original high alkalinity (Fig. 24). Hydroxyl ions
produced at the cathode (reinforcement) re-alkalise the concrete from the
reinforcement towards the surface. The anode takes the form of wet sodium
carbonate slurry contained in a cassette on the face of the concrete. The sodium
carbonate reacts with carbon dioxide and water to move through the concrete
and, as it does so, attracts alkalis to the concrete surrounding the reinforcement.
The process is non-destructive.

3.5.5 Hidden corrosion

There are often little or no visible signs of evidence of reinforcement corrosion.
In such cases it is important to carry out investigation to determine its presence
or otherwise. This assessment process is described in more detail in Part 2 of this
series of short guides on historic concrete but is summarised below.

Assessment of risk of hidden reinforcement corrosion:

- Conduct a cover meter survey of the structure or elements to identify the depth of cover and areas of vulnerability

- Select points for further investigation where the depth of carbonation may present a corrosion risk

- Carefully remove samples of concrete using small-diameter cores in less obvious areas and/or micro-drilling of important surfaces

- Check the depth of carbonation using a phenolphthalein solution

- Where carbonation has penetrated to a depth equivalent to the depth of cover, remove a larger area of concrete to expose the whole circumference of the reinforcement

- Assess the extent and severity of surface corrosion

- Decide on the nature and extent of repair work required

- If depth of carbonation extends to the reinforcement but corrosion is only minimal consider the use of electrochemical treatments (cathodic protection or re-alkalisation)

- If corrosion is more severe but not widespread throughout the structure, cut back the concrete to expose the reinforcement, remove surface rust, thoroughly clean out and execute appropriate patch repairs. Apply an auxiliary anode attached to the reinforcement at the boundary of the patch.

3.6 Maritime structures

The conservation and repair of historic concrete structures in maritime environments present a number of specific problems not faced by buildings in milder environments. They are exposed to some of the harshest conditions (classified as 'extreme' in *BS EN 1504-9:2005*) as they have to withstand attack from salt-loaded wind and rain, the dynamic and abrasive action of waves, and constant wetting and drying within the tidal zone (Fig. 25). In addition, many of these structures continue to perform their vital functions, providing protection from the sea and resisting the wear and tear of daily working operations, in the case of harbours and sea walls (Fig. 26), or as tower supports for beacons, lights and the like.

Fig. 25 Buckie Harbour, Moray. Tall, circular, mass concrete light tower, 1878 (Category C-listed).

Fig. 26 Weathered steps on harbour wall. The cement matrix forming the surface has been eroded to expose the aggregate.

Maritime structures form a significant proportion of the listed concrete buildings in Scotland (*see* Part 1 of this series of short guides on historic concrete). Their conservation and repair require a thorough understanding of the deterioration processes, the original materials and mixes, loading conditions and past repairs before appropriate design, specification and repair methods can be implemented. This, together with the monitoring of repair work, must be carried out by specialists in the repair of historic concrete in such environments.

Comprehensive advice on the maintenance and repair of concrete in maritime structures is provided by the *CIRIA Report C674* (Dupray *et al.*, 2010). When faced with the task of implementing repairs to such structures, it is recommended that the guidance provided in the CIRIA report is followed. Some of the key points from the report are summarised below in Table 3 to provide an overview of the issues and to provide a focus on potential conflicts with conservation needs. This table is reproduced from the CIRIA report but has been amended to include additional guidance on the potential impact of the recommendations on the conservation of historic concrete.

	UW	T	S	OW	D
Applying mortar by hand	✕	▲	✓✓	✓✓	✓✓
Recasting concrete	▲	▲	✓✓	✓✓	✓✓
Spraying concrete or mortar	✕	▲	✓	✓	✓
Replacing element	▲	▲	✓✓	✓✓	✓✓
Inspection of cracks	✕	▲	✓✓	✓✓	✓✓
Restoring cover: replacing mortar/concrete	▲	▲	✓	✓	✓
Replacing damaged concrete	✕	✓✓	✓✓	✓✓	✓✓
Re-alkalisation: electrochemical	✕	✕	▲	✓✓	✓✓
Re-alkalisation: diffusion	✕	✕	▲	✓✓	✓✓
Chloride extraction: electrochemical	✕	✕	▲	✓✓	✓✓
Replacing or supplementing corroded rebar	▲	▲	✓	✓	✓

KEY

✓✓	Generally suitable for historic concrete	UW	Underwater works
✓	Generally suitable for non-historic concrete – may be difficult for historic concrete	T	Tidal zone
		S	Splash zone
▲	Challenging	OW	Over water zones
✕	Generally not suitable	D	In the dry

Table 3. Options for repair works related to defects in historic concrete and concrete reinforcement with reference to their applicability to the maritime environment (adapted from CIRIA report C647, Duprey *et al.*, 2010, which was adapted from Tables 1 and 2 of EN 1504-9:1997, now replaced by BS EN 1504-9:2005).

4. Summary

The key issues discussed in this short guide are summarised below in Table 4. This table also includes reference to structural upgrading, which requires the expertise of engineers. This table should not be used in isolation but read in conjunction with the relevant text in other parts of this publication.

Issue	Summary	Maintenance and repair options	Conservation impact
Maintenance	*Routine on-going maintenance is inevitable as it is difficult to predict all potential hazards. Includes treatment of minor cracks and surface cleaning.*	*It is essential for all concrete buildings. Accessibility for routine maintenance and repair of underwater concrete is generally very difficult and may not be possible.* *Clean surfaces only when appropriate.*	*Routine maintenance is essential for continuing function and good conservation.*
Chloride-induced corrosion	*Can be a significant problem for all concrete but particularly for reinforced concrete in salt-laden environments.*	*Repair methods depend on the chloride content – coatings or corrosion inhibitors may be appropriate for low chloride content (i.e. before corrosion starts) but chloride removal may be required for highly contaminated concrete.*	*Coatings may change the appearance (section 2.2). Severe chloride-induced corrosion may require replacement of elements.*
Preparation for repair	*Before repair, restoration or upgrading, removal of degraded concrete and reinforcement cleaning may be required.*	*Careful preparation is essential and concrete removal may be by hand tools or mechanical equipment.*	*Concrete removal method needs to consider potential impact on adjacent concrete and preservation of historic finishes.*
Repair and restoration processes	*This should include consideration of both structural and material scale.*	*Structural repair options include those required to restore structural condition and stability (e.g. replacing elements with matching precast or cast in situ concrete).* *Restoring performance: restoring or improving drainage systems, junctions/joints, recasting slabs, restoring protection systems.*	*Restoration of structure conditions and stability should endeavour to match replacement of existing concrete with like for like, where this does not compromise the structure.*
Repair materials	*The selection of repair materials must be well considered after careful analysis of existing conditions.*	*Material options for concrete include the application of a repair mortar (usually a cementitious mortar): poured, pumped, sprayed or grouted.* *Restoring reinforcement passivity can be achieved by replacing concrete cover, replacing damaged concrete, re-alkalisation, chloride extraction or replacement of corroded reinforcement (avoid galvanised steel).*	*Sprayed concrete is particularly useful for maritime structures but could lead to difficulties in matching of surface finishes. See section 3.6 for treatment of reinforcement.*

Issue	Summary	Maintenance and repair options	Conservation impact
Surface protection	*Concrete surfaces can be 'protected' to help prevent further deterioration or to improve performance.*	*Protection of concrete includes protection against water ingress, controlling water run-off, controlling moisture levels, improving concrete resistance to physical or chemical attack, improving resistance to mechanical attack, e.g. abrasion or impact. Protection of concrete reinforcement can include restoring or preserving passivity, increasing resistivity, cathodic protection and control.*	*Any application of 'waterproof' or wearing surfaces that are essential for continuing utility should, wherever possible, be reversible and not result in the permanent loss of historic material.*
Structural upgrading	*Can consist of increasing the structural performance through improved geometry, strength or loading capacity.*	*Options include enhancing reinforcement, using carbon fibre composites, increasing physical dimensions and grouting to increase strength.*	*All of these methods have the potential to destroy the character of the historic structure. Only to be considered as a last resort after all other options have been explored.*

Table 4. Summary of maintenance and repair issues (adapted from CIRIA Report C674, Duprey *et al.*, 2010).

The maintenance and repair of historic concrete can range from routine inspection and simple, regular cleaning of the structure, to the full replacement of elements if required. It is important, prior to any work commencing, to gauge the appropriateness of the intervention on a case-by-case basis. A number of factors, such as the significance of the structure, its age, its projected life, the severity of the deterioration and the cost of remediation will all play a role in the decision-making process. The impact of the intervention on the heritage character of the structure as a whole must be considered.

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