5

Short Guide

Historic Concrete in Scotland Part 2: investigation and assessment of defects

Historic Scotland
Alba Aosmhor

National Conservation Centre
Ionad Glèidhteachais Nàiseanta

HISTORIC SCOTLAND
ALBA AOSMHOR

NATIONAL CONSERVATION CENTRE
IONAD GLÈIDHTEACHAIS NÀISEANTA

ISBN 978-1-84917-166-3

Principal Author: Dennis C M Urquhart

Published by Historic Scotland, March 2014

Historic Scotland, Longmore House, Salisbury Place, Edinburgh EH9 1SH

Historic Scotland would like to thank Steve Wood of David Narro Associates and Lucy O'Connor for their contribution to this publication.

Contents

1. Introduction

This short guide, the second of three on the subject of historic concrete structures in Scotland, discusses the investigation and assessment of defects of historic concrete. The first volume addressed the history and development of historic concrete in Scotland during the period 1840 to 1945, when concrete gradually came into widespread use. Part 3 of this series on historic concrete describes approaches to the maintenance and repair of historic concrete, which should be considered after investigation and assessment.

This guide relates to historic concrete prior to what we now know today as modern concrete (concrete produced after 1945), the production and application of which is governed by strict design and engineering codes. Concrete is a composite of a cementing material or binder (natural cement in the form of hydraulic lime or Portland cement), aggregate and water. Within this guide three types of historic concrete are referred to: mass concrete which is cast *in situ* (on site) using shuttering (formwork); precast concrete, which consist of concrete elements poured and formed off site, e.g. concrete blocks; and, reinforced concrete which is concrete with embedded metal to increase its tensile strength. Precast concrete discussed in this guide is not reinforced.

Given the age of the concrete structures under discussion (pre-1945), decay and deterioration of the material is, in some cases, inevitable. It is highly advisable, as concrete is a structural material, that specialists are engaged to carry out the investigation and assessment processes outlined within this text. It should be noted that there is extensive published information on the investigation and assessment of defects of concrete and this short guide is not intended to be a substitute for these publications. A list of references and further reading is provided at the back of this guide.

2. Concrete defects and decay

Before repair work is carried out on historic concrete structures it is essential that the current condition of the concrete is fully understood and the causes of any defects and decay of the concrete and any embedded reinforcement are established. In order to do this the composition of the concrete, including any embedded reinforcement, needs to be ascertained. Identification of these causes is often difficult because these may be the result of several inter-related factors. The majority of factors which cause decay in historic and modern concretes are very similar. Both will be affected by poor workmanship, aggressive environments and poor detailing. The latter can, in external situations, lead to uncontrolled run-off and increased penetration of rainwater. The presence of water is the primary cause of deterioration and decay in concrete.

Although many historic concrete structures will show at least some degree of decay and deterioration, is it actually remarkable how well these structures have stood the 'test of time', often having received only rminimal maintenance. Many of the structures are more than a hundred years old; even some reinforced concrete buildings are of this age. Problems often occurring with historic concretes relate to the design and construction principles at the time of their erection, which are unlikely to be relevant for modern concrete structures erected using current technical standards.

When dealing with defects it is important to distinguish between those that are applicable to concrete as a material, which may be found in mass, precast and reinforced concrete, and those that are a result of the introduction of ferrous metals into the concrete i.e. essentially defects in the reinforcement itself.

2.1 Defects in mass, precast and reinforced concrete

2.1.1 Effects of poor workmanship

The effects of poor workmanship are directly related to a lack of knowledge and experience of the material, and occur especially in cases where buildings were constructed by local builders experienced in constructing traditional masonry rather than concrete. Nevertheless, poor workmanship (by today's standards) could occur on large projects, even if supervised by architects or engineers.

Workmanship deficiencies are due mainly to:

- Unsuitable mix proportions
- Inadequately designed and supported formwork
- Inappropriate curing
- Inadequate compaction
- Lack of control of temperature extremes


1a

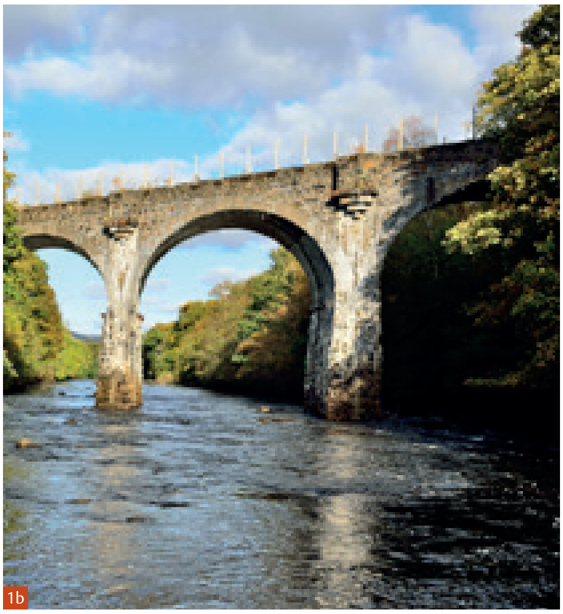

1b

Fig.1a and **Fig.1b** Dochart Viaduct 1885-6, second oldest mass concrete viaduct in Britain (Category A-listed), © John Gray.

Workmanship deficiencies can result in a reduction in density and durability, excessive permeability and shrinkage cracks, all of which can promote water ingress and corrosion of reinforcement. Inadequate cement binder and too much water in the mix can result in weak concrete, segregation and increased shrinkage.

In the case of pre-1914 concrete structures, concrete was often poured into formwork in short, vertical lifts because of constraints imposed by the lifting and placing techniques available at the time. As a result, there could be well-defined lift lines between pours and sometimes shrinkage cracks occurring at these points. Compaction at this time would have been achieved by ramming, tamping or 'punning' by hand which would often not achieve full compaction, especially around reinforcement. Without mechanical compaction, the obvious solution was to use a wetter mix so that it flowed more readily. In 1918, Duff Abrams formulated 'Abrams' law' which declared that the water-cement ratio was a fundamental determinant of concrete strength (Bussell, 2001). Mechanical compaction did not become common practice until the 1920s.

One of the earliest examples of mass concrete construction in Scotland is the Dochart Viaduct built over the River Dochart at Killin, Stirling in 1885-6 for the Caledonian Railway (Fig. 1). This Viaduct consists of five concrete arches of two feet thickness (approx. 610mm), each spanning 30 feet (approx. 9m) (Chrimes, 2001). The arches, each constructed in one day, were built up in six inch layers (approx. 150mm) using a concrete mix of 1:5 cement to crushed rock. The exposed walls, parapets, abutments and piers were constructed of various layers of stone rubble and concrete. Plain concrete was used for the fill between the masonry walls.

Caution needs to be exercised when assessing the effect of formwork. Poorly constructed formwork can result in surface bulges, honeycombing of the surface and ridges due to leakage of the mix between boards. Whilst these would be considered a defect in new concrete, in terms of historic structures they might be considered a preservable 'feature'. The presence of such features in a historic structure, which has survived for many years, should be considered part of the character of the building and a tangible link with its past. Unless they pose a serious risk to the building, such features should be retained.

However, where wide open joints have formed due to formwork related defects this may allow the penetration of water and more rapid erosion of the binder, disruption due to freeze-thaw cycles and/or reinforcement corrosion.

Original surface defects in historic concrete are considered to be part of the character of the building and should be retained unless they are contributing to on-going decay.

When a smooth surface finish was required a more cement-rich mortar coat was applied to the exposed face of the base concrete, after the shuttering (formwork) was removed but before the concrete had gained full strength (Gaudette and Slaton, 2006). Early precast concrete and, indeed, more modern precast units were often produced in this way. The cement-rich outer layer produced a smooth surface which was also used to provide an increased water-resisting layer. With the passage of time, surface weathering and surface cracking can permit moisture penetration resulting in de-bonding between the facing mortar and the backing concrete. This process can proceed rapidly as the cement-rich layer breaks down. Sometimes a cement-rich coat was applied to the backing concrete after it had dried substantially, and in such cases de-bonding is also liable to occur (Fig. 2).

2.1.2 Quality of aggregates

The quality and type of aggregates used can cause defects in the concrete, and poorly graded aggregates can lead to poor workability. The shape of the aggregate material is also important, as it affects its cohesive ability. Shrinkable or porous aggregates that are susceptible to moisture movement and freeze-thaw cycles can result in internal stresses and cracking. In addition, contaminated aggregates (containing reactive minerals and deposits) can cause poor bonding with the cement binder and may also result in corrosion of reinforcement.

When dealing with historic concrete it is important to understand that the role of the aggregate was not fully understood at the time. Heavy, bulky materials were not typically transported over long distances, so aggregates were often sourced locally. There may also have been a lack of local facilities to crush aggregate, other than breaking it up by hand. In many cases, the aggregates used historically would not be considered suitable by today's standards (Fig. 3).

Fig.2 Shuttered mass concrete wall with an applied smooth cement finish on a theatre building, constructed in 1872 (Category A-listed).

Fig. 3 The wall is poorly graded with large stones.


02


03

Fig. 4 shows an area of disintegrated concrete on a harbour wall from c.1890. It illustrates the nature of the aggregate, which is of local origin, poorly graded with large stones (up to approximately 100mm) and possibly hand-compacted into the formwork. The precast concrete in Fig. 5 contains beach shingle aggregate which has been exposed because the cement binder has been eroded from the face of the block, most likely due to the inclusion of marine salts (chlorides) within the mix.

2.1.3 Drying shrinkage – lack of movement joints

Drying shrinkage in concrete is part of the hardening process and should not be detrimental. However, when the shrinkage or foreshortening of elements is restrained, tensile stresses are produced and cracking may occur; thus the need for designed movement joints as determined by current technical standards. Early designs often did not fully allow for this potential movement. Designers and constructors who were used to lime-mortar bonded masonry (where the construction itself was capable of absorbing movement within the joints), did not have sufficient information to be aware of this issue.

Such cracks need not be a cause for alarm as once drying out has been completed, and the environment around the element has stabilised, the cracks will cease to move. Excessive, rapid drying of the surface can also produce surface crazing, which takes the form of a maze of fine cracks that are not usually structurally significant. Both forms of cracking are referred to as ‘non-structural cracks’.

04

Fig. 4 Concrete harbour wall constructed from locally available aggregate, built c.1890.

05

Fig. 5 The exposed aggregate in a precast concrete dressing. The aggregate is beach shingle with shell fragments, built c.1900.


06


07

Fig. 6 Shrinkage cracks in a mass concrete wall, built c. 1880.

Fig. 7 The core removed from this mass concrete wall shows the crack penetrating through both the cement render and underlying concrete. Building constructed 1872 (Category A-listed building).

The lack of movement joints in mass concrete Scottish buildings is ubiquitous, and examination of such buildings will usually reveal a pattern of cracks, most of which are not structural. This does not mean that all cracks should be ignored; they may be more than just surface cracks and extend through the whole width of the wall. Therefore, the overall pattern of cracking needs to be assessed and understood.

The main issue with respect to historic concrete is whether the exposed cracks allow ingress of moisture to accelerate the gradual breakdown of the exposed surface, corrosion of the reinforcement or lime leaching. The cracks shown in Fig. 6 and Fig. 7 are typical, often occurring at points of weakness such as openings.

2.1.4 Creep

Resulting from sustained stress which tends to build up over months or years, creep in concrete is a time-dependent issue due to sustained loading on the concrete. This can occur in reinforced concrete columns, slabs and beams where creep will shorten the compression zone, and result in increased deflections in these elements. As this deflection is not due to overloading, rather sustained loading, the element is not being overstressed. The deflections may, however, cause cracking of partitions below the beam or slab if this has not been considered in the structural design of the reinforced concrete.

It is important when dealing with the conservation of concrete structures to be aware of the different forms of cracking so that unnecessary remedial work is not embarked upon to deal with long-standing non-structural cracks.

2.1.5 Excess of free lime

All cements have, to some extent, an excess of free lime but this is potentially a greater issue with early cements. Free lime that has not been used in the setting and hardening processes can be taken into solution in soft water (Scottish water falls into this category) and then leached from the concrete to form calcium carbonate or calcium sulfate on the surface. Dochart Viaduct (Fig. 1) has suffered from the leaching of free lime on its surface. If the concrete surface is porous, or contains fine cracks, and is exposed to moisture movement this constant leaching can lead to a loss of surface cement and its gradual disintegration. Stalactites can form at joints and cracks where serious leakage of water occurs.

2.1.6 High alumina cement (HAC)

High alumina cement (HAC) is a calcium aluminate cement (also known in France as '*ciment fondu*'), being composed of calcium aluminates rather than calcium silicates. Patented in France by the Pavin de Lafarge Company in 1908, the cement material includes bauxite, an aluminium ore. This was introduced to take advantage of its rapid strength development and to improve sulfate resistance. Full strength could be achieved in 24 hours as compared to 28 days for OPC (Ordinary Portland Cement). However, the hydration reactions of calcium aluminate cements are very complex, with hydrates decomposing to a mixture of gel and water in a process called 'conversion'. This reaction sometimes results in a reduction in strength and increased vulnerability to chemical attack, especially in conditions of high humidity. The use of HAC concrete was effectively banned from use in new structural-concrete construction in the UK after some well publicised building collapses in the 1970s.

It is unclear how much use was made of this cement in Scotland in the early to mid-20th century but, unless the environment to which the concrete is exposed has changed, any problems, should HAC be present, are likely to have been discovered and addressed.

2.1.7 Alkali silica reaction (ASR)

There is a problem relating to aggregates known as alkali aggregate reaction (AAR) of which ASR is the best known example. This is a chemical process in which alkalis, usually from the cement, combine with certain types of silica in some aggregates, and which in the presence of water form an expansive alkali-silica gel. The expansion can cause star-shaped cracks, disruption of the concrete and white gel-like deposits of silica to appear on the surface. These reactive aggregates are now well known, and are no longer used. Given that this short guide relates to concrete structures that pre-date 1945, it is most likely that affected buildings would have demonstrated symptoms of this problem long before the present, and have been rectified.

ASR was not identified until the 1940s in the USA, with the first recorded case in the UK in 1971. The best known ASR problem in Scotland was the Montrose Bridge (Fig. 8), built c.1930, which was around 75 years old at the time of its demolition in 2004 (Doran, 2001). Defects due to ASR are unlikely to be a serious problem in existing Scottish historic structures given the elapsed time and the limited sources of reactive aggregates.


08

Fig. 8 Montrose Bridge, reinforced concrete cantilever construction. An unusual design for concrete construction (now demolished). SC 519533 © RCAHMS (Reproduced Courtesy of John R Hume). Licensor www.rcahms.gov.uk

2.1.8 Additives

It was common practice in traditional earth and clay-based structures to add materials such as straw, heather, broom, flax, hair, bristle and dung to the mix in an attempt to provide added bulk and increase binding (Walker and McGregor, 1996). When mass concrete work was introduced experimentation occurred by adding similar organic materials to the early mixes. Of course, these were detrimental to the concrete and reduced its durability.

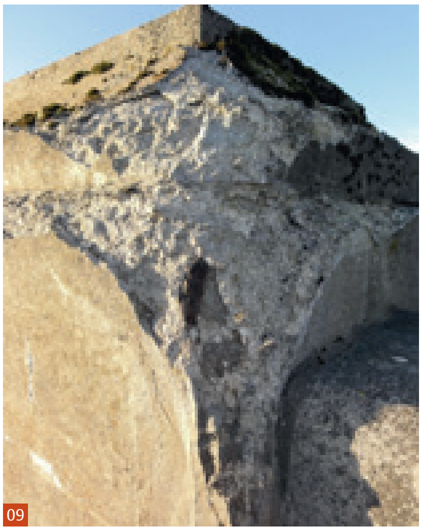
2.1.9 Environmental impacts

Lime-based binders, including Portland cement, are susceptible to attack by acids that are present in the surrounding environment including atmospheric pollution and acidic soils. Atmospheric pollution may contain both acids and sulfates. An acidic atmosphere also promotes a gradual breakdown and discolouration of the surface cement film. This may be unsightly, but is not usually of structural significance. The action of sulfates from the atmosphere and from the soil or ground-water can cause surface disintegration. Unless the cover to reinforcement is reduced this is not usually sufficient to cause structural problems. The most frequently found atmospheric sulfates (salts) are calcium sulfate ($CaSO_4.2H_2O$) and sodium sulfate (Na_2SO_4) (Amoroso and Fassina, 1983). These crystallise as salts within the pores and disrupt the concrete. The effect of this is illustrated in Fig. 9 where salt action may be a contributory factor in the decay process. This figure illustrates the corner of a reinforced concrete parapet feature which, due to its increased ratio of surface area to internal concrete volume, is more vulnerable to moisture penetration, road-salt spray and freeze-thaw cycles.

Chloride salts are extremely dangerous to concrete structures and, once in solution, they are very mobile and can penetrate and break up many crystalline structures. Three ways in which chloride penetrates concrete, particularly concretes which are quite porous, are through rising dampness in walls, marine aerosols transported by the wind and road de-icing salt. The most common chlorides likely to be present are calcium chloride ($CaCl_2$), halite (NaCl) and sylvite (KCl). Chlorides are particularly common in coastal regions and near roadways or paved surfaces because of desalting of surfaces during wintertime. The presence of chlorides can have onset consequences, such as the corrosion of reinforcement (see section 2.2.3). An example of concrete affected by chloride is shown in Fig. 10.

Fig. 9 Salt-induced deterioration of concrete on a reinforced concrete bridge, built c. 1930s.

Fig. 10 Concrete deterioration as a result of chloride attack, bridge built c. 1937 (Category B-listed).


09


10

Understandably, the effects of potentially harmful substances in the atmosphere and soil were not fully understood (if at all) in the design and production of concretes up to the mid-20th century.

Salts from the surrounding environment are particularly damaging to concrete, both reinforced and unreinforced. Most common salts present are:

- **Calcium sulfate**
- **Sodium sulfate**
- **Calcium chloride**
- **Halite (sodium chloride)**
- **Sylvite (potassium chloride)**

2.1.10 Climate conditions

Certain climate conditions, heavy rain, frost or changes in temperature can lead to cracking at the surface of the concrete. Damage by freeze-thaw action is the most common weathering-related defect, as ice crystals exert pressure within the concrete pores, causing surface cracks. Thermal stress can occur when the concrete constituents expand and contract due to temperature change, typically affecting mass concrete and causing minor surface cracking.

2.2 Defects of embedded ferrous metal in concrete

2.2.1 Reinforcement and other ferrous metals

The design of embedded metal (reinforced) concrete structures requires a good understanding of the behaviour of this composite material, particularly with regard to the positioning and anchorage of the reinforcement. Design-related defects in the reinforcement often become apparent early in the life of a structure when failure would be most likely. Consequently, the structure would either not have survived or would subsequently have been rectified to remain in use. One such design-related defect was the under-reinforcement or over-reinforcement of structures before calculation methods became more accurate.

In early structures, cast iron and wrought iron were used as reinforcement. While cast and wrought iron are more resistant than mild steel to corrosion, the combined effects of the more porous early concrete and the greater volumetric expansion of the corrosion products of iron mean the resultant disruption of the concrete can be severe. Rolled wrought iron sections (often cast into the concrete over openings) are liable to severe delamination in corrosive environments.

In older structures insufficient concrete cover was sometimes provided to the reinforcement, leading to an increased risk of reinforcement corrosion and associated cracking and spalling. There are particular problems resulting from inadequate concrete cover in buildings constructed during the 1940s because the Codes of Practice (technical standards) of the time recommended a depth of cover considered inadequate by today’s standards (Beckmann and Bowles, 2004).


11


12

Fig. 11 Inadequate cover to the steel reinforcement has resulted in corrosion and spalling of the concrete.

Fig. 12 Reinforcement corrosion, Lion Chambers, Hope Street, Glasgow, 1905 (Category A-listed).

The concrete deterioration shown in Fig. 11 is relatively recent and is likely to become a significant problem for the structure as there is evidence of spalling, indicating that steel reinforcement corrosion is developing rapidly. Fig. 12 shows cracking occurring due to reinforcement corrosion. Many of the historic reinforced concrete structures in Scotland are exposed to extreme or very severe environments. Nowadays, for new construction in such environments increased concrete cover is required as set out in *BS EN 1992-2:2005* (British Standards Institute, 2005). The current minimum requirements for concrete cover to reinforcement are contained within *BS EN 1992-1-1:2004* (British Standards Institute, 2004).

Corrosion of reinforcement is perhaps the most common cause of decay and reduced durability in concrete structures. Dealing with the effects of corrosion and the implementation of appropriate conservation and repair methods on historic buildings and structures demands knowledge and experience of the chemical and physical processes involved, if appropriate repairs are to be devised and achieved.

2.2.2 Carbonation

Hydraulic cements, which are alkaline in nature, when used in a concrete matrix offer a degree of protection against reinforcement corrosion. The hydration process which the cement undergoes produces alkaline compounds. In fresh concrete the matrix is strongly alkaline, with a pH between 12.6 and 13.5. The alkalinity provides ‘passive protection’ to embedded reinforcement. As the concrete ages, the alkalinity of the concrete is lost at the exposed surface as it comes into contact with atmospheric carbon dioxide and sulphur that produces acidic solutions in moist conditions. The reactions that reduce the alkalinity of the concrete, and thus its corrosion protection, are referred to as carbonation. This is a gradual process, and eventually the reinforcement is exposed to the risk of corrosion, which happens in the presence of air and moisture (Fig. 13).

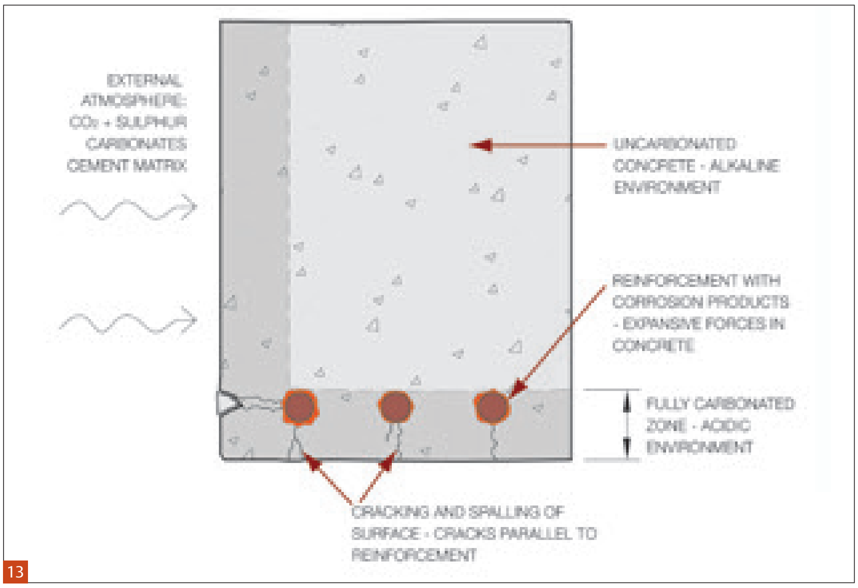


Fig. 13 Cracking of reinforced concrete due to corrosion of the reinforcing steel (or iron in historic concrete). Carbonation has occurred allowing moisture and air to penetrate.

The rate of carbonation of a concrete is primarily dependent on the:

- Permeability of the concrete
- Extent and depth of cracking (including micro-cracks)
- Ambient humidity (50-75% relative humidity (RH) is the critical range)

With the passage of time the depth of the carbonation and the permeability of the concrete increases. These processes affect the durability of the concrete covering the reinforcement. In the case of historic concrete, carbonation-exacerbated corrosion will become more prevalent as the concrete ages (Fig. 14).

2.2.3 Other additives

Calcium chloride was sometimes added to the mix to prevent freezing, yet chloride ions destroy the passive oxide layer on the reinforcement and encourage corrosion. Even as late as the 1950s it was thought that a small addition of calcium chloride would assist hardening in freezing conditions without adverse effects on the concrete, but this practice was banned in the UK in 1977 (the effect of chlorides in concrete is discussed earlier in section 2.1.9).

In the latter half of the 19th century aggregates composed of materials such as coke breeze, cinders, burnt clay, broken brick and clinker were used, as they were thought to be fire-resistant, having gone through fire. These materials were often quite acidic, due to the presence of sulfates, which increased the potential for corrosion of embedded metal.

Fig. 14 Carbonation combined with lack of cover has led to subsequent reinforcement corrosion on this floor slab.

3. Investigation and assessment

3.1 Investigation methodology

The investigation and assessment of the condition of the building or structure, while requiring specialist expertise, should follow the well-established sequence that applies to all historic buildings.

Concrete is principally a structural material and, therefore, a structural appraisal will be required to interpret the significance of the deterioration or possible additional loads due to a proposed change of use. The investigation and assessment of a historic concrete building or structure should be carried out by persons who are experienced and qualified in structural concrete analysis and conservation. There are likely to be cases where an architect, or even a conservation architect, will not have the suitable expertise to properly investigate and assess the structure, and it will be necessary to employ specialist advice, for example from a civil or structural engineer who specialises in historic buildings and/or a building pathologist with experience in concrete assessment, at least for parts of the project.

Formal consents are required for listed or scheduled structures. However, it is sometimes the case that building owners or their advisors will commission specialist concrete contractors to carry out repairs, or they may directly approach the manufacturer of specialist repair products. The danger with this approach is that the specialist contractor or manufacturer may not have an understanding of the significance of the conservation issues relating to the building or structure, particularly if it is not protected under some form of legislation. As many contractors use repair systems for which they hold a licence there will be a tendency for these contractors to recommend their own system before a full investigation has been carried out. This procurement approach should therefore be avoided.

It is advisable to ensure that the appropriate consultants appointed are independent so that any potential conflict of interest does not arise between the conservation needs of the building and the commercial interests of material suppliers and contractors.

Usually after information has been gathered from preliminary tests, a more detailed testing programme must follow, to eliminate or confirm possible causes of decay (G.B. Geotechnics Ltd., 2001). The cost of conducting an investigation and assessment should not be underestimated and should be fully allowed for in the overall cost of the project. An appropriate methodology is required, which is outlined in sections 3.1.1 to 3.1.3.

3.1.1 Selection of specialist consultants

In all but the simplest and least complex of cases**,** it will be advisable to appoint a specialist consultant or consultants. Depending on the nature of the structure and type of deterioration specialist advice may also be provided by civil/structural engineers with conservation experience, a cement chemist or a building pathologist with experience of historic cements and/or a corrosion specialist. The specialists should be able to advise on the type of tests that may be required to properly understand the nature and extent of the problem. These early appointments become even more important when repairs need to be carried out as quickly as possible and specialist contractors may also need to be commissioned.

3.1.2 Collection of historical information

Investigation should involve finding a range of historical information which may include:

a) Original project documentation, including when available:
  - Drawings
  - Specifications
  - Written reports
  - Information on mix proportions
  - Binder type/s
  - Aggregates (sources of)

  This information may be available from the archives of the local authority, the original consultants if they are still in existence or the Royal Commission on the Ancient and Historical Monuments of Scotland (RCAHMS). However, it is likely that original drawings have been lost. Even when drawings are available these may not provide an understanding of structural behaviour sufficient for assessment of changes of use or loading.

b) Information on any later investigations, assessment, alterations or repairs.

c) Contemporary photographs and others taken during the life of the building or structure.

d) Contemporary publications such as professional journals, newspapers etc. Even if not directly referencing the building they could provide useful information on the design and construction procedures and practices of the time, and on similar buildings of the same age in the same geographical location.

e) Details of listed buildings and scheduled monuments from Historic Scotland and records from the national collection of buildings, archaeology and industry at RCAHMS. The latter may include buildings and structures not included in the listed buildings or scheduled monument register.

f) Conservation plans/statements.

The collection and analysis of this information will contribute to the assessment of the heritage significance of the building and its construction, providing a better understanding prior to the site investigation. It may also give an indication of possible tests that may be required and could reduce the extent of specialist investigation required. In some cases a structural survey may be required to determine how the building was constructed and detailed.

3.1.3 Visual assessment

Even in situations where comprehensive historical information is available, a site investigation is essential to establish the overall condition of the building as it exists, and to identify the nature of any defects. It will also provide an indication of any differences between the 'as built' situation and the available drawings or specifications.

The first task is to conduct a visual condition survey (assessment) to obtain an overall understanding of the character and context and to indicate those areas that will require more detailed investigation and testing. This survey is useful to help build up a picture of the design and environmental factors that may be contributing to the decay processes.

The survey should examine how water impinges on, and flows over, the surfaces. Routes of penetration into and percolation through the structure may also be clarified at this stage, although these might need to be confirmed by subsequently opening up portions of the building as part of the diagnostic investigation.

The initial survey should be followed up with a more detailed visual survey of the location and nature of the areas of deterioration together with the type, position and extent of visible defects. These should be accurately recorded using site notes, photographs and sketch diagrams where appropriate. Detailed mapping of the defects, such as spalling, delamination, cracking, depth of decay, presence of salts, rust staining, reinforcement cover and exposure (where visible) and other signs of deterioration can give useful information regarding the seriousness of the problem.

The survey should also identify and record the location, nature and condition of any previous repairs that have been carried out. It is helpful if the approximate age of these can be established as this may indicate the nature of the materials that were likely to have been used. Also to be noted is any evidence that the repair has had a deleterious effect on the surrounding concrete.

It is helpful at this point to note the apparent cause or causes of deterioration. In the case of cracking it is particularly important to understand the underlying causes and not just the symptoms of the defect. Selection of the correct repair technique depends on knowing whether the cracking is due to repeated thermal cycling, accidental overloading, drying shrinkage, inadequate design or construction, or some other cause (American Concrete Institute, 2007). However, firm conclusions as to the cause of defects should only be drawn once all investigations and testing have been completed. The assessment of the evidence from this visual survey can be used to establish a theory for the type of deterioration and decay present, and also to design an appropriate, cost-effective and focused testing programme to be carried out on site.

On completion of the survey, it is useful to compare the condition of the defects with evidence from earlier photographs and records, if available, as this can provide a 'timeline' to indicate the rate of decay. Particular attention needs to be paid where there is evidence of worsening defects, for example an increase in crack width or length may be indicative of continuing movement.

3.2 Diagnostic investigation

When dealing with the conservation and repair of historic concrete it is likely that some form of diagnostic investigation will be required to supplement the visual survey results. The scope and extent of this diagnostic investigation will be determined by three factors:

- The heritage significance of the building or structure
- The scale and nature of the decay
- The availability of funding

Because the behaviour of many historic concrete structures is complex it may not be easy to initially define what is required for an accurate structural analysis. Complexity is increased as a result of problems of movement, vibration, stability or deterioration during the life of a structure. Therefore, it is often necessary to include structural monitoring, essentially the monitoring of movement, as part of the diagnostic investigation.

A diagnostic investigation will normally call for the appointment of a specialist, who would ideally have been already involved in the visual assessment on site, to identify the testing regime that will provide the information required to assist in achieving the most appropriate repair solutions. It is also important to be able to identify the presence of any latent defects that could affect the long-term performance of the concrete.

For a proper assessment of the problems, it will be necessary to carry out non-destructive tests and, in some situations, destructive tests. It is not the intention of this guidance to describe such tests in detail but to simply outline the more commonly used types of tests and their purposes. A comprehensive description of non-destructive investigations is contained in Historic Scotland's *Technical Advice Note 23 Non-destructive Investigation of Standing Structures* (G.B. Geotechnics Ltd., 2001).

As well as on-site non-destructive tests, laboratory testing on concrete samples might be required to supplement, or confirm, the site investigation. The extraction of samples for testing will be destructive to some degree. Such samples can be in the form of lumps (which may often be easily detached from decayed surfaces), cores (diameters usually ranging from 20mm to 100mm) or debris from small-diameter drilling. The position of large-diameter core removals may need particular consideration due to their consequential visual impact on the structure.

3.2.1 Non-destructive/non-invasive tests

A range of non-destructive, or non-invasive, on-site tests can be applied to help determine details of hidden parts of the structure such as the location of reinforcement, depth of cover and other conditions. Non-destructive tests may not be able to determine where corrosion is taking place but might indicate where there is potential for corrosion. A small core hole or some degree of 'opening up' may be required to calibrate non-destructive testing. In some cases it may be possible to use existing openings, such as openings used for services. Some of the more common non-destructive tests are outlined below.

Surface sounding

Hand-held hammer

The simplest of these tests uses a hand-held hammer, or other metal implement, to tap the surface to help identify areas of surface delamination and underlying voids.

15

Fig. 15 Elastic surface rebound hammer (Schmidt hammer) Chris Wood © English Heritage.

Schmidt rebound hammer

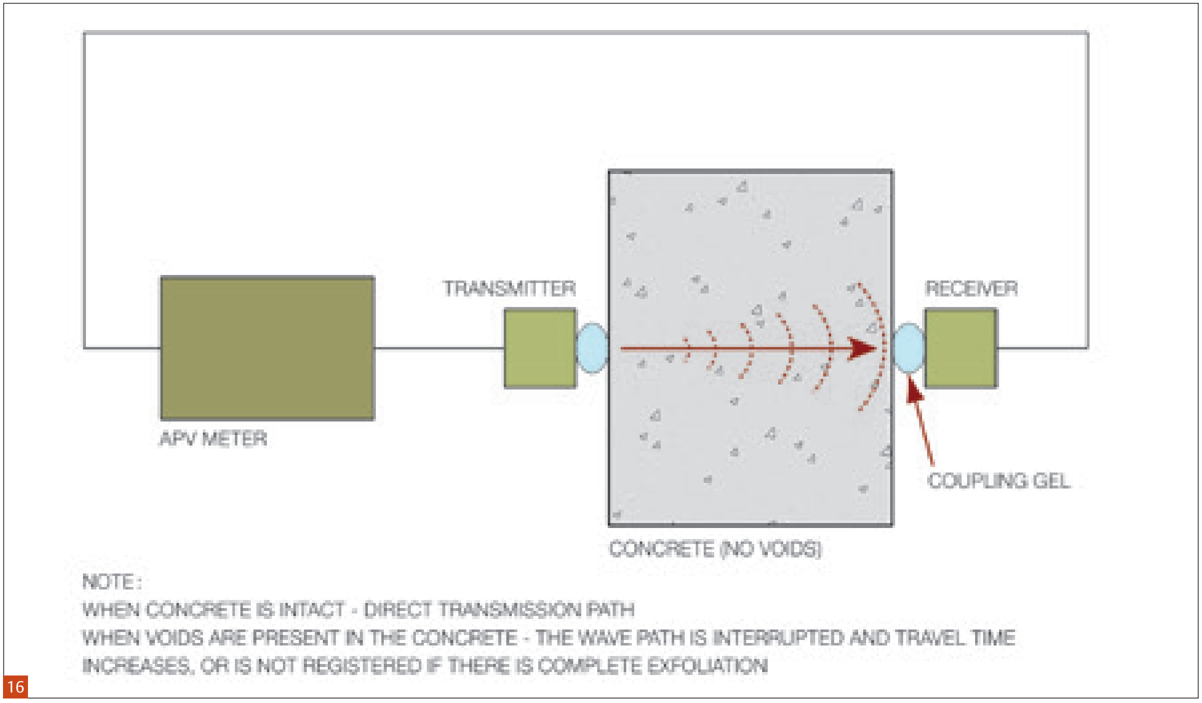
A more sophisticated technique is where a spring-loaded metal plunger is pressed against the surface of the concrete and further pressure causes the plunger to rebound (Fig. 15). The 'kick back' of the plunger provides a measure of the hardness of the surface and an indication of the concrete strength using conversion factors provided with the instrument. This is a simple and robust instrument, although the results should be treated with caution as they need to be confirmed by other means. The results might provide an indication of locations where more invasive tests using core or drilling samples should be taken. Testing should be carried out in accordance with *BS EN 12504-2:2001* (British Standards Institution, 2001).

Ultrasonic testing – surface velocity

Ultrasonic testing is a non-destructive method which uses pulse velocity to determine differences in the physical characteristics of materials. Two transducers are placed either side of an object or, where only one surface is accessible, on the same side. The equipment transmits and detects ultrasonic pulses and can be used to determine characteristics such as compressive strength and crack depth.

The test involves the placing of a transducer, or probe, on either side of the concrete element and the transmission of an electronic pulse through its thickness from the transmitting probe to the receiving probe (Fig. 16). The transmission time of the pulse provides a sensitive indicator of variations in compressive strength. The technique requires a skilled and experienced operator, as the presence of reinforcement can produce a false reading. Testing should be in accordance with *BS EN 12504-4:2004* (British Standards Institution, 2004).

Fig. 16 Ultrasonic pulse velocity test in operation.



NOTE:
WHEN CONCRETE IS INTACT - DIRECT TRANSMISSION PATH
WHEN VOIDS ARE PRESENT IN THE CONCRETE - THE WAVE PATH IS INTERRUPTED AND TRAVEL TIME INCREASES, OR IS NOT REGISTERED IF THERE IS COMPLETE EXFOLIATION

16

Impulse radar

This technique, also known as ground-penetrating radar, uses radio waves which penetrate the concrete. It was first developed to map near-surface geological formations and can be used to obtain information relating to the condition of construction elements. It is particularly helpful for use with mass concrete for the identification of changes in the condition of the material, such as the presence of cavities, voids and micro-cracks, and in the assessment of the bond between materials. A particular advantage is that it can be used on fragile and decaying surfaces. The accuracy of the results can be affected by features such as closely spaced or overlapping reinforcement, and materials with high moisture content. More information on impulse radar can be found in Historic Scotland's *Technical Advice Note 23 Non-destructive Investigation of Standing Structures* (G.B. Geotechnics Ltd., 2001).

Impact-echo test

The impact-echo test uses a small steel sphere to provide an impact-generated pulse (sound wave) that passes through the concrete structure and is reflected by flaws within the structure and external surfaces to be picked up by a transducer (Fig. 17). The test method is used to determine both thickness and flaws in elements such as slabs, wall beams and columns. One of the principal advantages is that it can detect the location as well as the depth of flaws in a concrete element.

Impulse response test

Impulse response tests are used for assessing the condition of large concrete structural members such as floor slabs, bridge decks, walls, tanks etc. It can be used for fast screening of larger areas to determine local areas with possible flaws, including delamination caused by steel corrosion, which can then be subjected to detailed analysis or coring for visual calibration to the test results. The impulse response test uses an impulse hammer with a built-in load cell that sends a pulse through the element. The impact is approximately a hundred times the force produced by the impact-echo test. The movement or velocity of the surface dynamic bending is recorded with a velocity transducer or geophone (Clausen, Nikolaos and Knudsen, 2012).

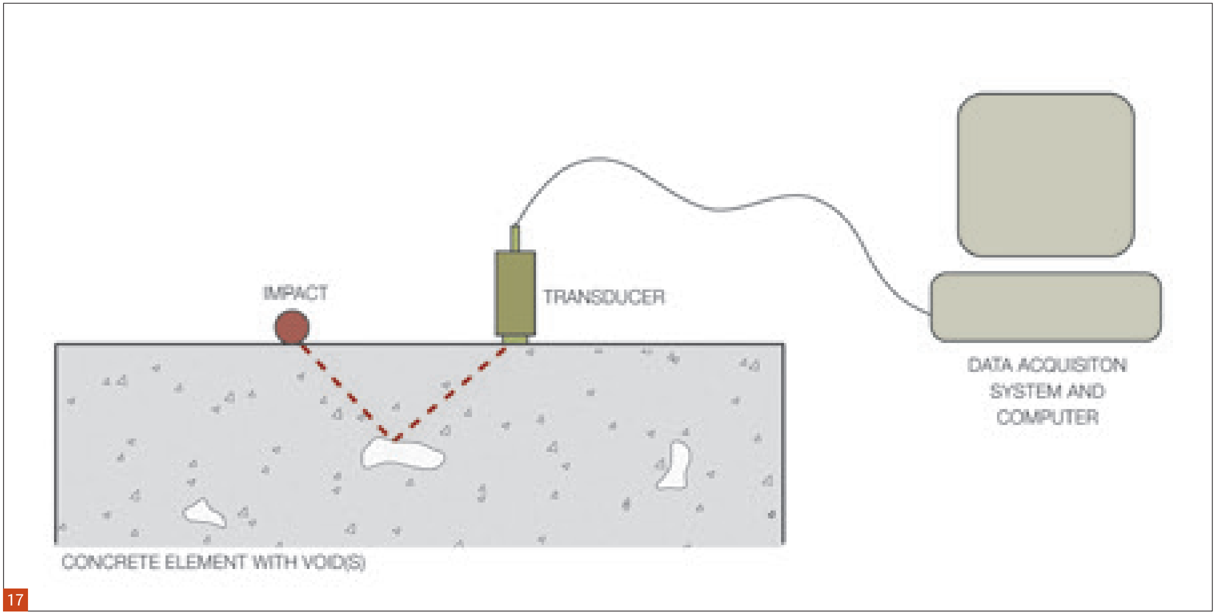


Fig. 17 Simplified diagram showing the impact-echo test arrangement.

Measurement of cracks

The history of the building or structure may provide evidence of existing cracks. A visual comparison with this historical evidence may be sufficient to assess whether or not there is continuing movement or deterioration. If there is doubt about the stability of the crack, there are a number of well-established ways, of varying sophistication, in which the crack can be measured and monitored. These techniques can range from simply attaching a piece of tape across the crack to proprietary strain gauges and transducers (for measuring stresses, deflections, static and dynamic loads, temperature and humidity). The use of a crack monitoring gauge such as a 'glass tell-tale', is perhaps the method most familiar to building professionals but, once the glass breaks, assessment of movement between the broken faces is inadequate for most purposes.

Reinforcement cover and location

The risk of concrete spalling due to corrosion of the reinforcement is a function of the depth to which the concrete cover to the reinforcement has been carbonated. Measurement of the depth of cover, and its location, will provide useful indications of the potential risk to the durability of the concrete and any latent problems. There are portable, hand-held electromagnetic instruments available, known as cover meters, which can indicate reinforcement cover depth from about 6mm to 90mm (*BS 1881: Testing Concrete,* (British Standards Institution, 1986, 1988, 2001, 2004)). This measurement can then be compared with the depth of carbonation to help estimate the potential risk of reinforcement corrosion. As with most instruments of this type it requires an experienced operator and expert interpretation of the results.

3.2.2 Destructive/invasive tests

Any further in-depth evaluation of the concrete will usually require samples to be taken for laboratory analysis. The extraction of samples will inevitably cause some damage to the concrete, and care should be exercised in the selection of the number of samples and location of the sampling sites. Wherever possible, samples should be taken from positions that limit the visual disruption to the character of the structure but are still at locations that will provide representative results. In the case of listed buildings, statutory approval (Listed Building Consent) is likely to be required before any sampling is carried out. Reference should be made to *BS EN 12504-1:2009* (British Standards Institute, 2009) for information on core sampling of concrete. The types of tests that are typically employed are described below.

Cement and aggregate content

The basic procedure is to take a representative sample of the concrete (or mortar), crush it to a fine powder and dissolve it in acid followed by analysis using standard analytical techniques. The principal chemical compounds in Portland cement are based on oxides of calcium (lime), silicon (silica), aluminium (alumina) and iron, with their compounds present in the form of their hydration products. There are other compounds also present in smaller quantities, such as magnesia and sulphides, along with reaction products in response to ageing, weathering and any chemical attack. The amount of insoluble residue is also determined and is normally assumed to be from the insoluble aggregate component of the mix. Cement from before 1920 is often more complex in composition and is not the same as modern (present-day) cements. Also early concrete may have used hydraulic lime as the binder, or a blend of lime and cement, or in some locations included other forms of binder, such as Parker's cement, which can further complicate the analysis. Details of the test method are described in *BS 1881-124:1988* (British Standards Institute, 1988). The analysis should be supplemented by a petrographic examination (see petrographic analysis section below), to ascertain the binder components, i.e. cement, lime (or a mix of both) and aggregate type, which is essential where limestone or shell is present in the aggregate. The use of other analytical techniques may also need to be considered, particularly where the provenance of the binder is unknown, or blended binders are suspected in the concrete. The analysis of early concretes should ideally be carried out by analysts with experience in the examination of such historic materials.

Chloride ion concentration

The chloride ion is a significant factor in both the decay of concrete and reinforcement corrosion. A test for chloride concentration will therefore provide valuable information about the decay risk to the structure, and inform its future maintenance. The concentration is measured using standard wet chemical methods or by means of a standard chloride test kit. A depth profile of the chloride ion concentration is established by taking dust from drill samples at different depths (usually every 25mm), in accordance with *BS 1881-124:1988* (British Standards Institute, 1988). When the sampling is taken at the location of the reinforcement, the extent of the risk of reinforcement corrosion due to chlorides can be estimated. The small diameter of the drill means that this test is relatively unobtrusive. Analysis of the extract for chloride content using potentiometric titration is routine and inclusion of this in testing is widespread.

Depth of carbonation

This is a simple test that can be done on-site or in the laboratory using split core samples. The concrete is exposed in representative locations and the exposed concrete is sprayed with a solution of phenolphthalein in alcohol and water. The areas of concrete that are uncarbonated, i.e. still alkaline, turn the solution pink at $pH>9.5$, while there is no colour change in the carbonated areas. The results of the depth of carbonation test can be compared with information on concrete cover to the reinforcement to assist in an assessment of corrosion risk. It should be noted that carbonation around micro-cracks may not be readily revealed by the phenolphthalein spray. As with other forms of concrete analysis, this test, although simple, requires the skills of an experienced investigator to interpret the results.

Sulfate content

The sulfate content of concrete is an indicator that the concrete and reinforcement is at potential risk of deterioration, mainly through expansive chemical products of reinforcement corrosion. The gravimetric method in *BS 1881-124:1988* (British Standards Institute, 1988) remains the standard analysis for sulfate content of concrete. Concrete samples are obtained by drilling as described above.

Petrographic analysis

Petrographic examination of samples removed from the structure, in the form of cores or lumps of concrete, can provide information about the mineralogy and microstructure of the concrete. These are not chemical tests. Concrete petrography is most commonly carried out using an optical microscope to examine thin sections of concrete. It is best suited to the general examination of concrete to estimate the original water-cement ratio, porosity, homogeneity of the concrete mix, crack location and the overall mix proportions and identification of components. Also, carbonation, sulfate attack and alkali-silica reaction are some of the processes that can be identified with this analysis.

Of particular importance to reinforced concrete is the determination of:

- **Reinforcement cover**
- **Chloride ion concentration**
- **Depth of carbonation**
- **Sulfate content**

3.2.3 Other analytical techniques

Scanning electron microscopy (SEM)

Analysis of the microstructure of concrete can be a very important part of the assessment process. SEM uses electrons instead of light to scan a surface and is able to obtain high levels of magnification, beyond the range of optical microscopy. SEM is especially useful in the study of decay processes such as sulfate attack, alkali-silica reaction, alkali-carbonate reaction and any other situation where the microstructure or the micro-compositional characteristics of the concrete need to be examined. This technique can therefore provide important information about the microstructure of the concrete and the chemistry of the surface. It can also detect inorganic contaminants such as salts and metals. SEM is a laboratory-based analysis and requires samples to be taken from the structure under investigation.

X-ray diffraction (XRD)

This technique is not widely used for routine concrete analysis as it is best suited for identifying crystalline mineral phases. Because the most important constituents of concrete, including hydrated cement, are variously non-crystalline or poorly crystalline the application is somewhat limited (Crofts, 2006). However, XRD can be useful, for example, when it is necessary to characterise clays that may be present and their ability to be expanded by the absorption of water. It can also be used to identify products of decay such as salts. XRD analysis typically requires only very small samples.

Laser microprobe mass spectrometry (LMMS)

LMMS uses a laser to ionise a very small volume of the sample and is potentially minimally invasive. As a result it is a technique that is available to assist in the study of the chemical deterioration of a sample as it can detect both organic and inorganic species, for example the weathering of a surface crust, the presence of sulfates or staining of a surface (Leysen *et al.*, 1987). If the cause of surface staining can be identified using LMMS this may reduce the need for more invasive investigations of historic concrete and other surfaces. It can also provide important guidance on where further investigation is required and what form this should take.

3.3 Analysis, interpretation and reporting

Analysis of the decay and deterioration must be based on an accurate evaluation of all the evidence available from the historical documentation, the site investigation and the results and interpretation of all the testing undertaken. A preliminary analysis may indicate the presence of anomalies requiring further investigation or additional testing. Any such additional work should be done before final conclusions are reached and repair measures are implemented. As previously stated, relevant experience is an essential prerequisite.

The analysis and reporting should focus mainly on the deterioration but should also take into account the overall significance of the building, and the potential for remedial work to adversely impact on its character.

The investigation report should focus on:

- The causes of the deterioration or decay and not simply the symptoms
- The rate of progress of the decay and the impact or risk posed to the integrity or character of the building
- The consequences of not implementing the necessary remedial measures
- An assessment of any alternative solutions, including a cost-benefit analysis

4. Summary

There are many factors which contribute to the decay and deterioration of historic concrete: poor workmanship, poor detailing, the use of unsuitable aggregates, drying shrinkage, environmental impacts and, specific to reinforced concrete, the deterioration of reinforcement within the concrete. These factors can be difficult to assess and investigate, usually requiring specialist or professional survey and/or testing techniques. Understanding the structural form as well as the causes of defects and decay in the concrete is imperative before embarking on a repair or maintenance scheme. It is important to generate a detailed report of findings after the investigation and analysis phase is complete. Part 3 of this short guide series on historic concrete details the approaches to the next step: the maintenance and repair of historic concrete.

5. References and further reading

References

American Concrete Institute. (1996). *Concrete Repair Guide, ACI 546R-96*. Michigan: American Concrete Institute, (Reapproved 2001).

American Concrete Institute Committee 224. (2007). *Causes, Evaluation, and Repair of Cracks in Concrete Structures, ACI.1R-07*. In Manual of Concrete Practice Part I. (2010), Michigan: American Concrete Institute.

Amoroso, G. G., and Fassina, V. (1983). *Stone decay and conservation: Atmospheric Pollution, Cleaning, Consolidation and Protection.* In Materials Science Monographs, Amsterdam: Elsevier Science.

Beckmann, P., and Bowles R. (2004). Structural aspects of Building Conservation, (2nd ed.). Oxford: Elsevier Butterworth Heinmann.

British Standards Institution. (1986). *BS 1881-201:1986 Testing Concrete, Guide to the use of non-destructive methods of test for hardened concrete.* London: British Standards Institution.

British Standards Institution. (1988). *BS 1881-124:1988 Testing concrete, Methods for analysis of hardened concrete.* London: British Standards Institution.

British Standards Institution. (1988). *BS 1881-204:1988 Testing Concrete, Recommendations on the use of electromagnetic covermeters.* London: British Standards Institution.

British Standards Institution. (2001). *BS EN 12504-2:2001 Testing concrete in structures. Non-destructive testing – Determination of rebound number.* London: British Standards Institution.

British Standards Institution. (2004). *BS EN 12504-4:2004 Testing concrete. Determination of ultrasonic pulse velocity.* London: British Standards Institution.

British Standards Institution. (2009). *BS EN 12504-1:2009 Testing concrete in structures. Cored specimens. Taking, examining and testing in compression.* London: British Standards Institution.

British Standards Institution. (2004). *BS EN 1992-1-1:2004 Design of concrete structures. General rules and rules for buildings.* London: British Standards Institution.

British Standards Institution. (2005). *BS EN 1992-2:2005 Eurocode 2. Design of concrete structures. Concrete bridges. Design and detailing rules.* London: British Standards Institution.

Bussell, M. (2001). *The era of proprietary systems.* In Sutherland, R.J.M., Humm, D., and Chrimes, M., (Eds.) Historic Concrete: background to appraisal. London: Thomas Telford.

Chrimes, M. (2001). *The development of concrete bridges in the British Isles prior to 1940.* In Sutherland, R.J.M., Humm, D., and Chrimes, M., (Eds.) Historic Concrete: background to appraisal. London: Thomas Telford.

Clausen, J. S., Nikolaos, Z., Knudsen, A. (2012). *Onsite measurements of concrete structures using Impact-echo and Impact Response.* Emerging Technologies in Non-destructive Testing, V. Paipetis et al. (Eds.) London: Taylor Francis Group.

Crofts, D. (2006). Contemporary chemical techniques in concrete analysis. *Concrete*, April 2006, pp 40-42.

Doran, D. K. (2001). *Alkali Silica Reaction in Concrete,* Institution of Structural Engineers, London May 2001. Retrieved from: http://www. Instructe.org. [accessed 2011].

G.B. Geotechnics Ltd. (2001). Non-destructive Investigation of Standing Structures, Historic Scotland Technical Advice Note 23. Edinburgh: Historic Scotland.

Gaudette, P. and Slaton, D. (2006). *Preservation Briefs 15: Preservation of Historic Concrete.* Washington DC: Technical Preservation Services Division, National Park Service, U.S. Department of the Interior.

Leysen. L., Roekens, E, Komy Z, Van Grieken R. (1987). *A study of the weathering of an historic building (sic).* Analytica Chemica Acta, Vol 195, 1987, pp 247-255.

Walker, B., and McGregor, C. (1996). *Earth structures and construction in Scotland,* Historic Scotland Technical Advice Note 6. Edinburgh: Historic Scotland.

Further reading

Delft University of Technology. (1999). *Urban Heritage Building Maintenance – Concrete.* Delft: Publications Office Faculty of Architecture.

English Heritage. (2012). *Practical Building Conservation – Concrete.* London: MPG Books Group.

McDonald, S. (2003). *Concrete Building Pathology.* Oxford: Blackwell Science.

Newby, F. (2001). *Early Reinforced Concrete.* Vol.11. London: Ashgate Publishing.

Sutherland. J., Humm, D.,Chrimes. M., (2001). *Historic Concrete: background to appraisal.* London: Thomas Telford.

This publication has been produced using FSC® Mix certified stock and non-mineral oil-based inks. If you no longer need this publication please pass it on, recycle it or return to Historic Scotland.

HISTORIC SCOTLAND
ALBA AOSMHOR

NATIONAL CONSERVATION CENTRE
IONAD GLÈIDHTEACHAIS NÀISEANTA