

# The Investigation and Repair of Historic Concrete



 NSW  
Heritage Office



*The Investigation and Repair of Historic Concrete* was written by Susan Macdonald, Assistant Director of the NSW Heritage Office. Susan studied architecture and has considerable experience in heritage conservation, having previously worked in the Architectural Conservation Team of English Heritage. She has a particular interest in the conservation of 20th century buildings and materials. She is former Secretary of DOCOMOMO UK and a former member of the executive committee of ICOMOS Australia.



Bottle kilns similar to those used in cement production in the 19th century, photographed in 1889. Portland cement first began to be produced by Australian companies in the 1880s, including the Cullen Bullen Lime and Cement Company at Portland, NSW. *Photograph courtesy of the Cement & Concrete Association of Australia*

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*Front Cover:* One of the most significant uses of concrete in Australia was in the construction of the Sydney Opera House. Precast segments, post-tensioned together formed the ribs of the roof shells. The building was officially opened on 20 October 1973.

*Photograph courtesy of the Government Printing Office collection, State Library of NSW*

# The Investigation and Repair of Historic Concrete

This information sheet provides guidance on the repair of reinforced-concrete buildings. It looks at the causes of concrete deterioration and explains how to approach the repair of reinforced-concrete buildings. It also strongly recommends that a specialist structural engineer be consulted for independent expert advice. Such an engineer will need to have the necessary expertise in structural assessment, investigation and repair. A glossary is provided to explain some of the more technical terms used in this information sheet.



## Contents

---

**A brief history of concrete in Australia** 4

---

**Understanding the material and the structure** 5

---

Concrete: Composition and characteristics

**How and why concrete deteriorates** 6

---

Concrete decay

Causes of deterioration in reinforced concrete

**An approach to repair** 10

---

Assessment and investigation

Repair

Maintenance

Balancing technical performance, life-cycle costs and conservation

**Further information** 17

---

**Glossary** 18

---

# A brief history of concrete in Australia

**Despite being thought of as a modern material, concrete has been in use for thousands of years. Lime-based hydraulic cements (those set by chemical reaction with water) have been in use since Roman times. Some ancient mortars still survive today, including examples used in the Pantheon in Rome and aqueducts in France. The word concrete comes from the Latin *concretus*, which means “mixed together” or compounded.**

The use of these hydraulic mortars declined after the Romans but was revived during the Middle Ages. The technology survived until the eighteenth century when John Smeaton's experiments in England produced the first real advancement in concrete technology since early Roman times. This signalled the beginnings of the modern concrete industry.

Lime concrete was the precursor to modern concrete and was made with natural cements. In Australia the early use of what was described as concrete was, in fact, mainly lime concrete. Natural cements were initially imported to Australia from the 1840s and then from the 1860s were manufactured in Australia.

The first modern concrete was made with Portland cement. Portland cement was manufactured from limestone or chalk, together with clay or shale. It was patented by Joseph Aspdin in 1824 and named after its resemblance to Portland stone. It began to be produced in Australia in the 1880s. Towards the end of the nineteenth century modern concrete (using Portland cement instead of lime) began to be used for floors, foundations and infrastructure projects.

## Reinforced concrete

The principles of reinforcing concrete to provide both tensile and compressive strength were understood in ancient times. However, it was not until the nineteenth century that a number of European and North American inventors developed and patented reinforcing methods. This resulted in the widespread introduction of a fully fledged concrete industry.

Reinforced concrete construction was introduced into Australia in the early 19th century and by 1909 there were about six specialist companies using patented systems of reinforced concrete. The first reinforced concrete structure in Australia was the Johnstons Creek and Whites Creek Sewer Aqueduct built in 1895 in Annandale. It was constructed using Monnier's system of reinforcement (under license from the French company). This structure was recently repaired and still serves its original purpose for sewerage. The aqueduct is listed on the State Heritage Register in recognition of its significance as one of the first major reinforced concrete structures built in Australia.

Australia was quick to take up reinforced concrete. A number of reinforcing systems for floors and roofs were used, including straps and external forms. By 1915 the use of reinforced concrete began to be regulated.

It was not until the 1950s that prestressed concrete, which uses tensioned steel to increase strength, began to be used in Australia. After WWII structural steel was in short supply and prestressed concrete provided a substitute. The ice tower at Warragamba Dam is one of the earliest examples.

The use of concrete has changed dramatically over the last 100 years, and continues to evolve as understanding about the material improves.

The sewer aqueducts constructed at Johnstons Creek and Whites Creek in Annandale were Australia's first major reinforced concrete structures. They were built by Carter Gummow & Co. in 1895 using Joseph Monnier's reinforced concrete technique, under license from the French company.

*Photograph courtesy of the  
Cement & Concrete Association of Australia.*



# Understanding the material and the structure

**Just as the design of a reinforced-concrete building varies enormously according to its date, so does the construction method, materials and standards of workmanship. All these factors affect how the building deteriorates and may result in different problems, depending on when the building was constructed. It is thus imperative to understand the characteristics of a reinforced-concrete structure, in order to diagnose problems correctly and identify appropriate repair techniques.**

## Concrete: Composition and characteristics

Concrete is made up of sand or stone, known as aggregate, combined with cement paste to bind it. Aggregate can be of various sizes. It is broadly categorised as fine (commonly sand) and coarse (typically crushed stone or gravel). The greater proportion of concrete is aggregate which is bulky and relatively cheaper than the cement.

As much of the constituents of concrete come from stone, it is often thought that concrete has the same qualities and will last forever. Concrete has been called artificial stone, cast stone, reconstructed stone and reconstituted stone. However, concrete must be thought of as a distinct material to stone. It has its own characteristics in terms of durability, weathering and repair.

Concrete has high compressive strength, but weak tensile strength. To overcome this deficiency when concrete is used as a structural building material, reinforcement (originally iron and later steel) is included in areas where tension occurs. This also helps to combat early shrinkage and subsequent diurnal thermal expansion and contraction.

Steel and concrete have similar coefficients of expansion and contraction and therefore work well together as a composite material. Concrete is usually mixed wet, poured into formwork, which supports its wet weight, distributed around the placed reinforcement, and then compacted or vibrated to expel air. It then sets or hardens by chemical reaction.



The houses forming the striking streetscape of 258-266 Johnston Street, Annandale, were built by well known Sydney builder John Young in the 1880s. Mass concrete was used in the footings and turrets.

*Photograph courtesy of Anthony Mitchell*



Concrete was used for lighthouses and marine engineering works, such as Bradleys Head Lighthouse in Sydney Harbour. It was the first pre-cast concrete lighthouse in Australia. Constructed in 1905 by Gummow Forrest & Company, it is the earliest example of the use of reinforced concrete in maritime situations and utilises both in-situ and pre-cast sections.

*Photograph by David Nutley*

## Reinforced concrete

Concrete is nearly always reinforced with steel embedded within it. Reinforced concrete can be manufactured in a casting yard (precast concrete). But for buildings, it is more commonly made on site (in situ concrete). Its performance and appearance are therefore dependent on the individual materials of which it is composed, workmanship during construction, and on subsequent environmental conditions and maintenance. Improved quality control and mix designs, along with a now recognised understanding of some of the earlier degradation problems, has greatly reduced the chances of poor quality construction and premature degradation.

Unfortunately, a number of historic concrete structures exhibit problems that are related to their date of origin. Practice methods of the day, such as workmanship and understanding about best practice, can lead to concrete decay, as can materials in use at the time, including types of reinforcement, cement matrix and water content.

# How and why concrete deteriorates

**It is imperative to establish the cause of the concrete degradation or steel reinforcement corrosion before repairs are carried out. Poor understanding of the cause of the problem can result in inappropriate repairs.**

## Concrete decay

Concrete is a relatively durable and robust building material, but it can be severely weakened by poor manufacture or a very aggressive environment. Concrete degradation can be a cause for concern on its own, or in reinforced structures it may lead to decreased protection to the steel. This in turn encourages corrosion of the steel, often followed by cracking and spalling of the concrete.

Deterioration of concrete is due to either:

- chemical degradation of the cementitious matrix;
- corrosion of the reinforcement steel;
- physical damage (impact, abrasive and fire damage).

The most important causes of concrete deterioration are described below.

## Causes of deterioration in reinforced concrete

### Design problems

There are a number of design and specification problems that can result in reinforced-concrete deterioration.

Causes of the problem	Results
Poor reinforcement details, for example congested or inadequate reinforcement, inadequate cover to reinforcement	Leads to cracking, poor compaction, loss of alkaline environment, and voids around the steel
Poor detailing of fixings, window frames, handrails, supports, and expansion joints	Water penetration, localised cracking, and balcony weakness
Long, slender components	Excessive flexing may lead to cracking
Inadequate design for creep	Deflection due to strain under continued stress that can result in cracking
Decorative finishes, such as acid etching, bush hammering, and fluting	Results in varying depth of cover around the steel and localised corrosion
Poor drainage	Leads to water ponding and localised corrosion/degradation
Incorrect concrete grade for purpose	Can produce concrete that is too weak/too strong
Mixes that result in high drying shrinkage	Can result in cracking
Mixes that are permeable to chloride ions	Chloride induced reinforcement corrosion



Centennial Park Reservoir No 1., showing mass concrete groined arches and brick columns. The reservoir was completed in 1898 after nearly five years of construction time and was described as “by far the largest of its kind in the Southern Hemisphere”. The reservoir is still operating. Image RS/P/83 LP, courtesy of Sydney Water Corporation and Sydney Catchment Authority Historical Research and Archives Facility

## Workmanship

Care and attention during construction is crucial to the long-term durability of reinforced concrete. Current building codes, including AS 3600, give guidance appropriate to the exposure conditions, and on mix design (particularly the water/cement ratio and amount of cement binder), additives, compaction, detail, and thickness of cover. The type of cement binder is also now well defined. However, this has not always been the case and durability problems of earlier concrete are summarised in the following table.



Typical reinforcement corrosion resulting from inadequate depth of concrete covering to the reinforcement.  
*Photograph by Susan Macdonald*

Causes of the Problem	Result
Poor mixing	Leads to inhomogeneous concrete, localised weakness, and reinforcement corrosion
Incorrect water/cement ratios	Can lead to variable strength, inadequate durability, increased drying shrinkage, excessive permeability
Poor compaction/vibration	Results in honeycombing, voids, excessively permeable concrete, localised reinforcement corrosion
Varying and inadequate cover depths around the steel	Leads to localised reinforcement corrosion, penetration of damaging substances
Poor curing techniques	Results in shrinkage cracks, increased permeability, poor durability
Premature stripping of formwork	Can result in cracking

## Materials

Lack of knowledge about the importance of careful selection and specification of materials and the use of additives has created a number of durability problems for historic concrete structures. They can be the result of the use of the following.



Typical cracked concrete section due to poorly compacted concrete.  
*Photograph by Kevin Hunt*

Causes of the Problem	Result
Too low cement content	Results in weakened and poor durability concrete
Too high cement content	Can result in excessive shrinkage/poor workability and cracking
Additives, such as calcium chloride	Chloride ions destroy the protective passive-oxide layer on the steel
High alumina cement	Weakening concrete in wet environments
Too finely-ground cements	Causing excessive shrinkage and cracking that compromises the permeability of the concrete
Poor quality aggregates	Resulting in alkali-aggregate reaction, poor workability of the concrete, poor compaction, high drying shrinkage and weak concrete
Contaminated aggregates	Resulting in corrosion of steel and degradation of concrete in extreme cases
Poorly shaped and badly graded aggregates	Results in poor workability often necessitating extra water or vibration during forming which can lead to segregation, bleeding etc
Incorrect water/cement ratios	Giving rise to weak concrete, loss of durability, increased permeability to gases and chloride ions

### Environmental influences

These play an important part in reinforced-concrete deterioration and include the following.

Environmental condition	Result
Carbon dioxide and acidic gases	Lower pH around the steel that enables corrosion to progress
Water	Can introduce depassivating chloride ions into concrete
Freeze thaw in colder zones	Breakdown of surface, progressive cracking, water penetration to reinforcement that enables corrosion to progress
Salt ingress	Marine salt introduces depassivating chloride ions into the surface of the concrete
Chemical attack	Chemical attack by chlorides can cause corrosion of steel or sulphates that can cause degradation of the cementitious matrix
Vibration	Causes cracking, spalling, and delamination
Impact damage	Causes physical weakening of structural components, exposure of steel reinforcement, cracking etc

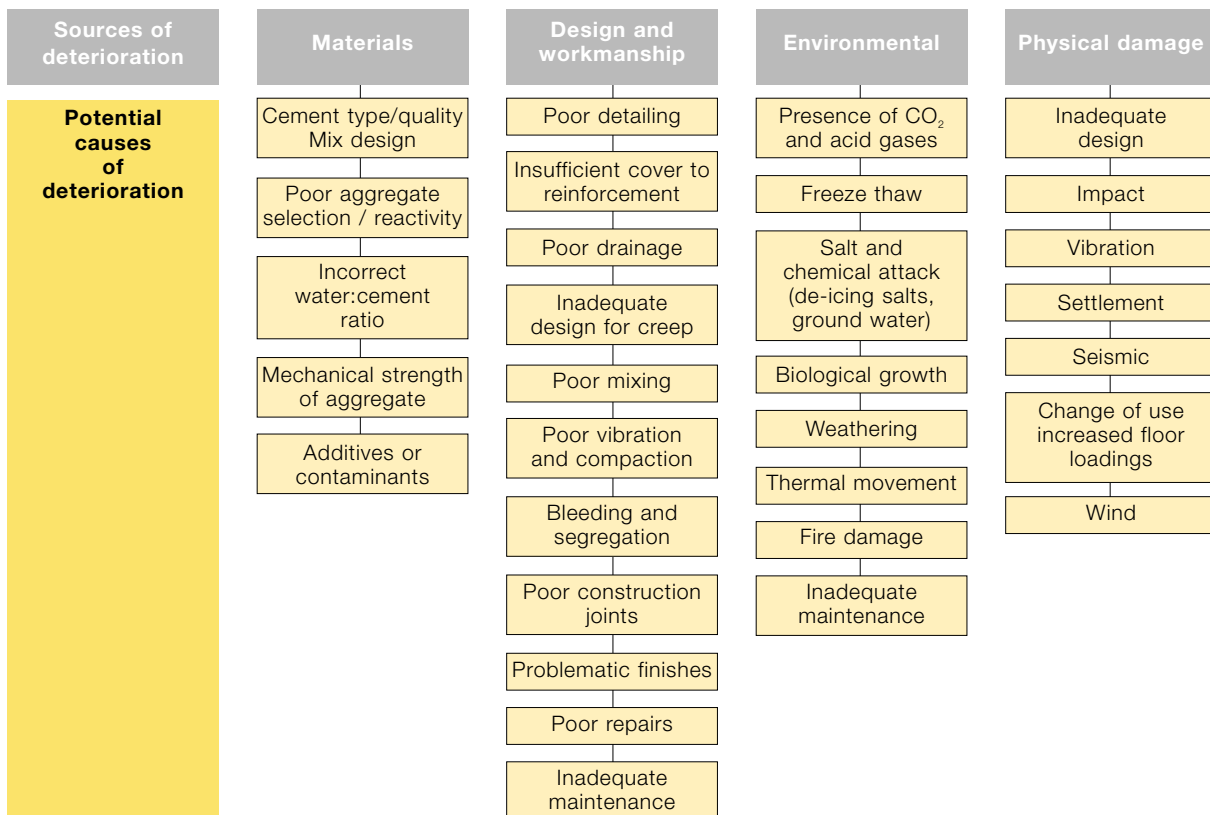
### Physical damage

Concrete structures can also be affected by physical damage, such as:

- excessive loads
- impact damage
- abrasion
- fire damage.

### Lack of maintenance and poor repair

When concrete first began to be used as a major structural building material, it was promoted as a material that needed little, or no maintenance. However lack of maintenance is a major contributor to reinforced-concrete deterioration.



The principal sources and causes of concrete deterioration.  
Table by Susan Macdonald

## Corrosion

The major cause of deterioration in reinforced concrete structures is corrosion of the reinforcing steel. Corrosion requires air and water to take place. The key to durability in concrete design is to have a mix and cover which ensures that the reinforcement is always well protected from these elements.

However, when corrosion occurs the same steel that gives reinforced concrete its tensile strength, is capable of rupturing the concrete. This is the result of the expansion in volume which takes place when steel corrodes.

There are two major causes of steel corrosion that can occur even without other degradation to allow water and carbon dioxide to track to the steel: carbonation and chloride attack.

### The corrosion process

Corrosion of steel in concrete is an electrochemical reaction in which the major constituent of steel (iron) goes into solution as iron ions with a flow of electrons (electrical flow). This site is called the anode. Electrons are produced in this self-sustaining process and flow through the reinforcement towards cathodic sites – where they react with oxygen and water from outside to produce additional hydroxyl ions. This is known as the cathodic reaction. There is no external source of electrons: the anode produces electrons at the same rate the cathode consumes them. This process is shown in the figure below.

The most common causes of steel corrosion are the loss of alkalinity around the steel as a result of carbonation and the presence of chlorides at the steel surface. Although both processes produce different forms of corrosion, carbonation and the presence of chlorides result in the loss of the protective passive layer around the steel and the commencement of the electrochemical reaction explained above. Both are also directly related to the durability of the concrete and its ability to prevent acidic gases destroying the alkalinity of the concrete, or to prevent chloride ions from migrating to the steel.

Harmful corrosion can occur in the presence of dissimilar metals that are linked by an electrolyte in the concrete; for example when zinc-coated steel is linked to uncoated steel or where there are copper pipes or aluminium fittings in the concrete.

**Carbonation** occurs when atmospheric carbon dioxide reacts with the pore water in the concrete creating carbonic acid, which reacts with the lime in solution ( $\text{Ca}(\text{OH})_2$ ) reducing the alkalinity of the concrete from 12.5 to less than 9.0. Carbonation is not harmful to concrete but when the carbonation front reaches the level of the steel reinforcement, corrosion will commence.

**Chlorides** may have been added to the concrete at the time of construction as a calcium chloride accelerator (used in cold weather, or to speed up turnaround of moulds and formwork), or cast in from poorly-washed marine aggregates, or may have ingress from sea water, wind-blown marine spray or saline groundwater. Chlorides attack the passive oxide layer of the steel but do not affect the alkalinity of the concrete.

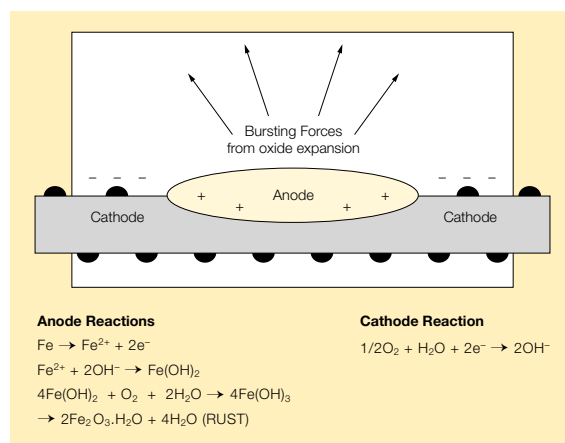
## Corrosion of the steel reinforcement

Most reinforced concrete deterioration is related to reinforcement corrosion either directly or indirectly as the result of other degradation. Reinforcement corrosion will usually result in the development of expansive rust products (hydrated iron oxides) that put the concrete into tension around the steel. This leads to cracking, and eventually spalling of the concrete. Degradation of the concrete matrix can result in loss of protection to the reinforcement steel and corrosion. The two mechanisms – chemical degradation of the cementitious matrix and corrosion of the steel reinforcement – may be initiated independently but become inter-related.

Cement paste is usually highly alkaline, containing mobile hydroxyl ions within the pore water that is always present. These hydroxyl ions ( $\text{OH}^-$ ) in the pore water coat the surface of the embedded steel reinforcement producing a strong passive-oxide layer. It is when this oxide layer is broken down, by the ingress of aggressive ions such as chlorides ( $\text{Cl}^-$ ), or not maintained by the high alkalinity (due to atmospheric carbon dioxide or attack by acidic gases), that corrosion can occur. The effectiveness of the passive layer in providing long-term corrosion protection to the steel is dependent on:

- the constituents of the concrete;
- the thickness and quality of the concrete forming the cover;
- the durability and permeability of the concrete forming the cover;
- the homogeneity of the concrete forming the cover;
- environmental conditions.

There are many good texts on corrosion of reinforcement, some of which are included in Further Information.



The corrosion of concrete-encased steel is an electrochemical reaction.

*Illustration courtesy of John B. Broomfield*