# Historic concrete structures in New Zealand

## Overview, maintenance and management

Department of Conservation
*Te Papa Atawhai*

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ABSTRACT

Early concrete structures form an important part of New Zealanders' cultural heritage. This handbook describes the historical development of concrete and its properties, and outlines the background to early concrete structures, concentrating on the early use of concrete (up to the 1940s) as a building material in New Zealand. It identifies characteristic defects and patterns of deterioration in the material, and explains how these may be recognised and described. Concrete is a complex and varied material, and its production has become more sophisticated over time; thus, its manufacture, properties and uses were influenced by the knowledge and perceptions at the time of construction. Repair methods have also changed considerably in the last few decades and are still changing. As the components of concrete have been undergoing continuous development over the past 150 years, architects and engineers involved in the preservation of historic concrete structures need to understand the material of the period and the manner of its making and use. Therefore, a set of evaluation procedures and conservation strategies for the preservation and repair of these structures is proposed. This handbook is intended to assist those lay persons who have responsibility for administration of historic resources or whose duties involve making decisions about their care and maintenance.

Keywords: concrete technology, historic concrete, natural cement, Portland cement, hydraulic lime, pozzolans, plain concrete, reinforced concrete, defects, deterioration, repair, conservation


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# 1. History of concrete

## 1.1 ORIGINS AND DEVELOPMENT OF CONCRETE

The Romans are well known for their extensive use of concrete more than two millennia ago, yet experience and knowledge of *cement*[1] materials is still developing and expanding. Scientific research into cement and concrete technology surged dramatically from the beginning of the 20th century with the growing use of steel-reinforced concrete, but even today, almost 180 years after the first patent for *Portland cement*, many gaps in our understanding remain. Concrete has been one of the most widely used building materials over the past 100 years. It has made possible numerous complex structures, ranging from bridges, monuments and buildings, to civil engineering works.

The earliest use of concrete dates back to before 5600 BC: a 250-mm floor slab from this period, which was made using a red lime, *sand* and gravel mix, has been discovered on the banks of the Danube in Yugoslavia. In Egypt, murals dating from 1950 BC show various stages of the process of making concrete (Stanley 1980). The first concrete used was mass or plain concrete, which exploited its great strength in compression. This was produced using limestone, which was burnt to form lime or *natural cement*. To make concrete that would set and harden, the lime had to have sufficiently high *hydraulic* properties; that is, the concrete had to be able to set in water or when exposed to only a small amount of air.

*Hydraulic lime* was obtained by using impure limestone that contained a significant amount of clay, or by the addition of naturally occurring volcanic ashes, or *pozzolans*, to ordinary lime. Both types of cement were very variable in their properties. The Romans used lime concrete extensively in their building works. Roman concrete was used principally as a filling in brick or stone masonry walls, into which the pozzolanic cement, made from lime and pozzolanic ash, was poured over layers of broken stone and rubble until the structure was filled.

During the Middle Ages, the use of concrete declined, although isolated instances of its use have been documented and some examples have survived. During this period, lime with low hydraulicity continued to be used for *mortar*, plastering and lime washing.

Concrete was more extensively used again during the Renaissance and its manufacture was described in a work by De Lorme, published in 1568 (Gwilt 1881). At this time, mass or plain concrete was used in structures such as bridge piers. Pozzolanic materials were added to the lime, as done by the Romans, to increase its hydraulic properties (Thornton 1996).

In the 18th century, with the advent of new technical innovations, a greater interest in concrete developed. In 1759, John Smeaton experimented with types of limestone collected from many parts of Britain. He discovered that lime that was made from limestone containing a significant proportion of

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[1] See Glossary for definitions of technical terms (shown in italics).

clay would always produce a *hydraulic cement*. He decided to use blue lias, a moderately hydraulic lime, to which he added a pozzolanic material to achieve a very hard and hydraulic lime for the Eddystone lighthouse (Smeaton 1793: 181, cited in Swallow & Carrington 1995). This material was used in the base of the structure and in the bonding mortar of the masonry superstructure. (The lighthouse stood for 120 years until it became unsafe, due to the erosion of the rock on which it stood rather than any failure of the cement; Swallow & Carrington 1995.)

Smeaton's work was followed by Joseph Aspdin who, in 1824, patented the first 'Portland' cement, so-named because concrete made with the cement was similar in colour to Portland stone. In 1844, Aspdin's son James took over the business of producing cement, with the company bearing the family name until 1904. Although the American Obadiah Parker produced a very similar cement in the 1830s, for many years England was pre-eminent in producing and exporting Portland cement to the rest of the world, including India, Australia, New Zealand, South Africa, Canada and Russia. By the 1850s, English, French and German engineers were using Portland cement in docks, harbour walls and military structures.

In spite of these early engineering uses of the material, concrete did not develop as a general building material until the late 1800s. At first it was largely used as mass or plain concrete because of its inherent compressive strength. Artificial cements were then developed, in which carefully gauged proportions of limestone and clay were burnt to obtain specific properties. These concretes had much higher crushing strengths and lower porosities, as well as a greater degree of uniformity than the earlier hydraulic limes and natural cements.

The final advance was the development of reinforced concrete, which had greater tensile strength and was much more versatile for building and construction. The first experiments with reinforcing concrete, which used first wrought iron and later steel, started in the 1850s, although isolated earlier examples exist—for instance, the Pantheon in Rome (AD 125) is known to have bronze reinforcing in its dome; Christopher Wren used chains embedded in concrete to resist lateral thrust in the dome of St Paul's church in London, which was built between 1675 and 1710 (Jones 1913); and Thomas Telford used iron bars in the abutment of the Menai Straits bridge in 1826. Ralph Dodd took out one of the first patents on the use of wrought iron bars in concrete in 1818, and by 1850 numerous patents had been registered for combining iron with concrete.

A number of people experimented with iron mesh and rods in beams and slabs for buildings. Between 1870 and 1877, the American Thaddeus Hyatt was one of the first to realise the importance of anchoring the ends of the reinforcing rods, which he fitted with nuts and washers to prevent them from pulling out of the concrete. Hyatt used an elaborate lattice of flat iron bars with holes at intervals for transverse round bars in an attempt to increase the tensile strength of concrete slabs and beams (Fig. 1). He registered numerous patents, but never made a commercial success of his work (Jones 1913).

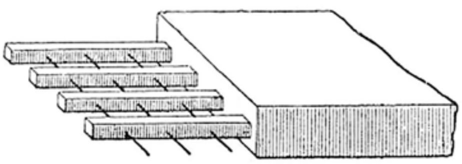


Figure 1. Hyatt system, applied at first to floor slabs and later also to beams (from Marsh 1905).

The principle of reinforcing concrete for general use was established in the late 1800s. Terms to describe this material included béton armé, armoured concrete, ferro-concrete (commonly used in New Zealand), and concrete steel. The term 'reinforced concrete' only came into general use later (Marsh 1905).

In 1892, François Hennebique, who is regarded as the French pioneer of concrete, patented a system of steel-reinforced beams, slabs and columns. Hennebique's patent proved to be one of the most popular and was used for a large number of structures built in England between 1897 and 1919, including buildings, bridges, viaducts, maritime structures, reservoirs, water towers and canal works. In Hennebique's system (Figs 2 & 3), steel reinforcement

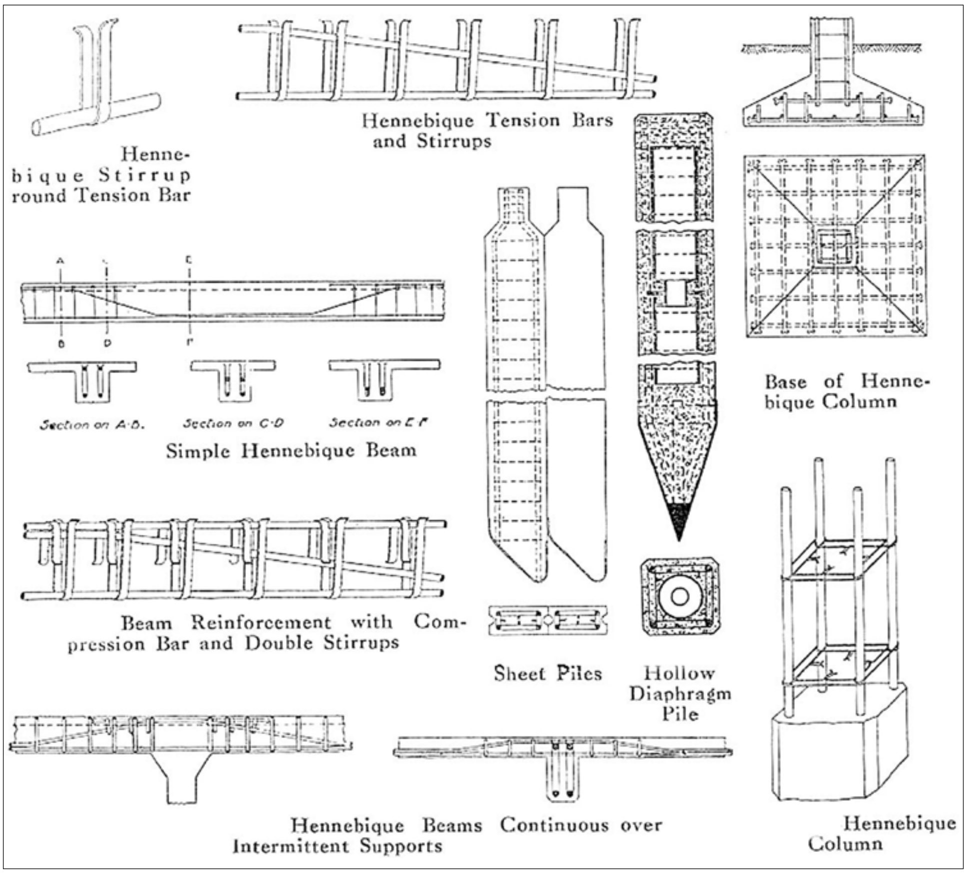



Figure 2. Hennebique system, showing general arrangement of reinforcement in beams (from Jones 1913).

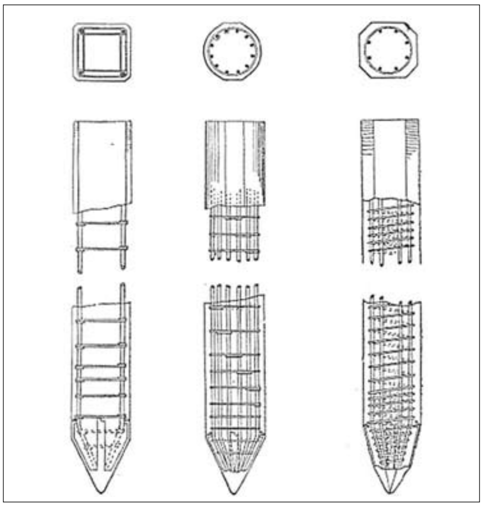


Figure 3. Types of early pile, from left to right: Hennebique square pile, Coignet round pile, Considère octagonal pile (from Marsh 1905).

was placed correctly in the tension zone of the concrete; this was backed by a theoretical understanding of the tensile and compressive forces, which was developed by Cottançin in France in 1892.

Ernest Leslie Ransome patented a number of improvements to reinforced construction, including expansion joints and the use of twisted bars to improve bonding (Figs 4 & 5). He built the first reinforced concrete bridge in the USA in 1889, and a number of warehouses and factories (Jones 1913). The elegance of Ransome's structures (Fig. 6) and their repetitive symmetry were much admired by later European architects (Thornton 1996).

Auguste Perret was another Frenchman who had a great impact on the use of concrete. In his church Nôtre Dame du Raincy he used tall, round, tapering columns with vaulted slabs and large areas of glazed, non-load-bearing walls. Gustav Maillart, a Swiss designer and pupil of Hennebique, developed the mushroom column and flat slab, and is noted for his elegant and adventurous bridges. Pier Luigi Nervi experimented widely with the possibilities that reinforced and precast concrete offered, and particularly applied these techniques to the construction of domed structures.

By the 1900s, concrete was generally used in conjunction with some form of reinforcement, and steel began to replace wrought iron as the predominant tensile material. A significant advance in the development of reinforced concrete was the pre-stressing of the steel reinforcing. The

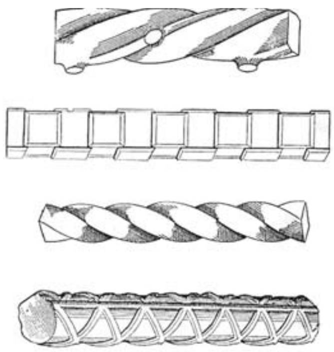


Figure 4. Examples of early steel bars designed to improve the bond between concrete and steel (from Kidder 1909).

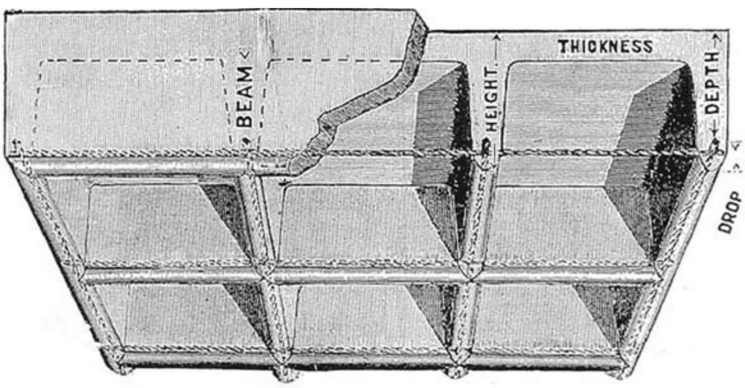



Figure 5. Ransome's system, which was widely used in the USA in the early 1900s, was similar to the Hennebique system, except for the use of square twisted reinforcing bars (from Marsh 1905).

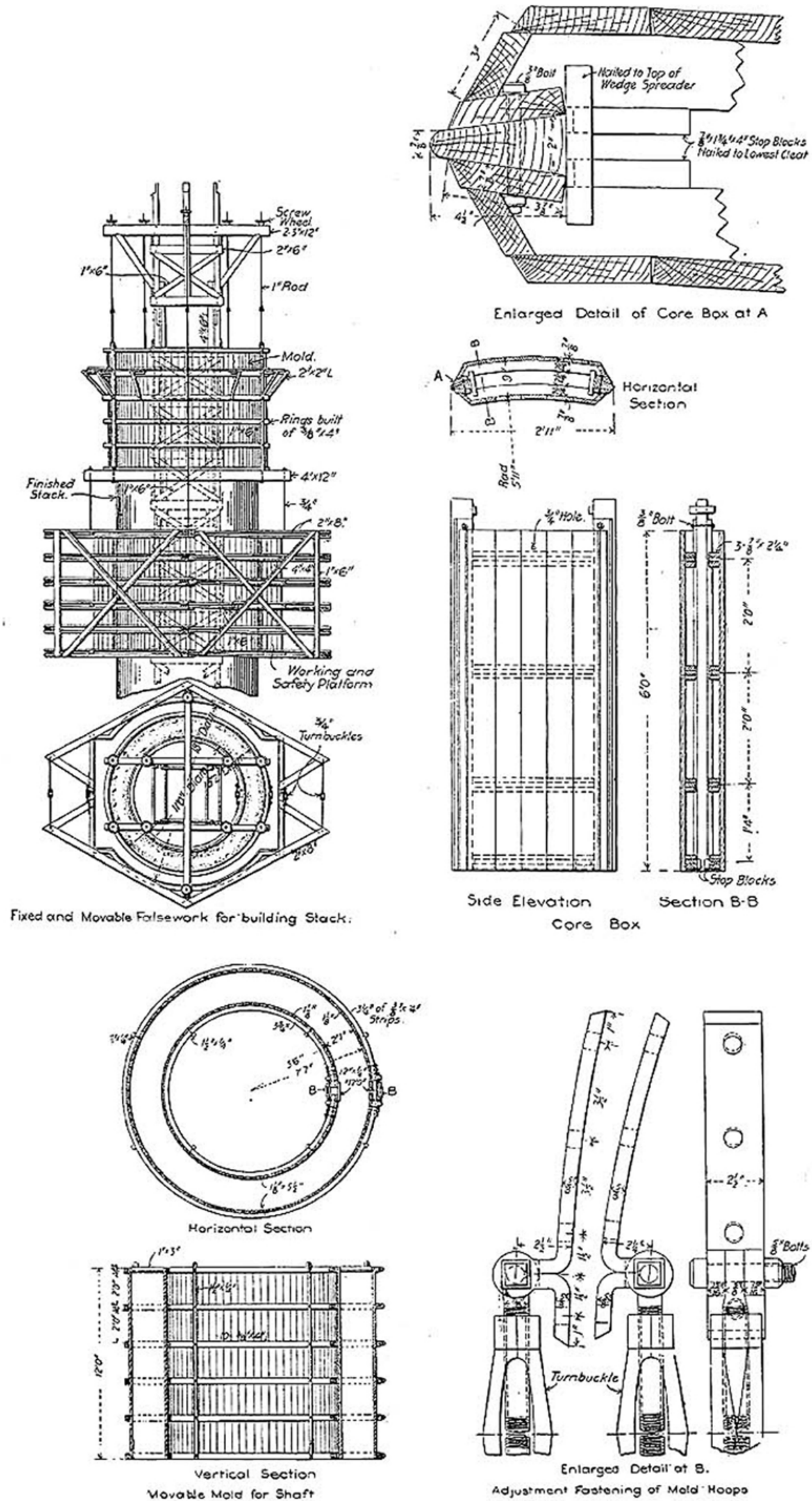



Figure 6. Shuttering and moulds used by Ransome's in 1903 for a reinforced chimney 165 feet high (from Marsh 1905).

earliest experiments date from 1886, when C.E. Dochring, a German builder, pre-tensioned iron wires. These experiments were unsuccessful, as high-tensile steel was not used and the concrete was not of a high enough grade for this type of construction. Further experiments in pre-stressed concrete were undertaken in the 1920s by Eugene Freyssinet, but the technique was not widely used until the 1940s. However, in 1929 the New Zealand Public Works Department used pre-tensioned No.8 wires in concrete fence posts (Thornton 1996). This was one of the earliest practical uses of what was essentially a form of pre-stressed concrete.

Reinforced concrete was generally cast *in situ* and this is still a widespread practice. However, in modern construction, precast concrete is widely used, to reduce construction times and to ensure greater accuracy and strength of concrete components.

## 1.2 USE OF CONCRETE IN NEW ZEALAND

Although New Zealand was relatively isolated in the late 1800s, a surprising amount of this newly developing technology was used here. Records show that casks of artificial cement were imported from England as early as 1843[2], and numerous concrete structures were built between 1840 and 1900, including many engineering and military structures, the scale and size of which increased with time. Private citizens and farmers built a large number of experimental buildings and structures, including settler houses and farm buildings. A wide range of lime, cement and aggregate was used, depending on what was available.

As occurred in Britain and the rest of Europe, the first use of concrete in New Zealand was predominantly in the form of plain or mass concrete, although a few isolated experimental attempts at reinforcing were undertaken from the 1870s. After 1900, New Zealanders embraced the use of reinforced concrete with enthusiasm. While Britain had strict building regulations and established masonry construction methods that stifled the use of concrete and resisted the changes brought by the new techniques, this was not the case in newly developing New Zealand.

There are probably several reasons for the wide use in New Zealand of what was, at that time, still an experimental building material: the rapidly growing country had urgent need of infrastructure; concrete was found to be a robust structural material comparable to both steel and timber; it could be constructed using a wide range of 'as-found' materials; there was a shortage of skilled tradesmen such as stonemasons and bricklayers, and concrete required less skilled labour; and it proved more durable and cost effective than either steel or timber in the often damp, humid environment. Early settlers seemed ready to experiment with new possibilities in this new environment, and concrete offered ways of making buildings fireproof and later, with reinforced concrete, earthquake resistant. Although timber was

[2] Thornton (1996) noted that the records did not specify whether imported cement was 'Roman' or 'Portland' cement. However, in 1843 Portland cement was not commonly used in England, whereas Roman cement was being produced in large quantities.

very widely used in the early colony, it was nevertheless not regarded as offering the sense of durability of traditional masonry, whereas concrete provided that sense of robust permanence.

Thornton (1996) described the wide and varied use of concrete in New Zealand between 1850 and 1939, highlighting many structures that were unique even in world terms. Thornton (1996) provided several examples of early concrete structures from the 1850s and '60s, including:

- A concrete cottage described in the Lyttleton Times 17 April 1852.
- The bridge piers and abutments of a bridge outside New Plymouth in 1859.
- The 1867 bridge over the Waiwakaiho River, built with concrete piers; the bridge was replaced by a reinforced concrete structure in 1907.
- A two-storey mass concrete house near Mosgiel, built in 1862 by John Gow, an early settler and farmer. Even by international standards, this is remarkable for its age and construction materials.

During the 1870s, numerous concrete structures were built in New Zealand, including the Oamaru breakwater, which was constructed of concrete blocks, each weighing 25 tons, and the shaft of the valve tower of the Karori reservoir, which was built in concrete in 1873 and is beautifully detailed with scrolled corbels to support the timber upper structure. Many large residences and farmhouses were also built using mass lime concrete.

The first attempts to use reinforcing in New Zealand were made in the 1870s, but the first real use of reinforcing is documented as the 18-m-high water tower at the New Zealand Railways workshops in Addington, Christchurch, which was built in 1883 and reinforced with tons of scrap steel; this was still recently in use (Thornton 1996).

From the 1880s onwards, the type and variety of concrete structures increased (Thornton 1996). Concrete was used in every form of building construction, including coastal fortifications; engineering structures, such as graving docks, lighthouses, bridge piers and water towers; factory and farm buildings; residential buildings; and public buildings, such as health facilities, schools, banks and religious buildings. Both lime and Portland cement concretes were used, still largely in the form of mass concrete. Until this time, almost all of the artificial cement used was imported, but this now started to change very gradually as lime and cement industries were established on a commercial scale.

The first concrete lighthouse in the world was built in 1873 in Jersey in the Channel Islands. New Zealand followed within a decade, constructing a concrete lighthouse on Burgess Island in the Hauraki Gulf in 1882. This was built using purpose-made concrete blocks that had to be winched to the summit, making it a pioneering use of precast concrete in this country.

The former Congregational church of St James in Beresford Street is a very early concrete construction that was built in 1876 and is still in use. In 1884, the former synagogue in Princes Street, Auckland, was built of mass concrete, using Roche lime produced locally near Warkworth. The mass concrete was then rendered internally and externally, a common finish for concrete buildings at the time. Recently restored and now used by the

University of Auckland, the building is in excellent condition. Many Catholic churches designed by the noted engineer/architect Frank Petre incorporated concrete in their construction, in some cases reinforced. His basilica church of St Patrick in Oamaru (1894) and Sacred Heart Cathedral in Wellington (1895) (Fig. 7) used mass concrete walls faced in Oamaru stone—the latter with hoop iron reinforcing. Petre's fondness for the material earned him the nickname 'Concrete' Petre.

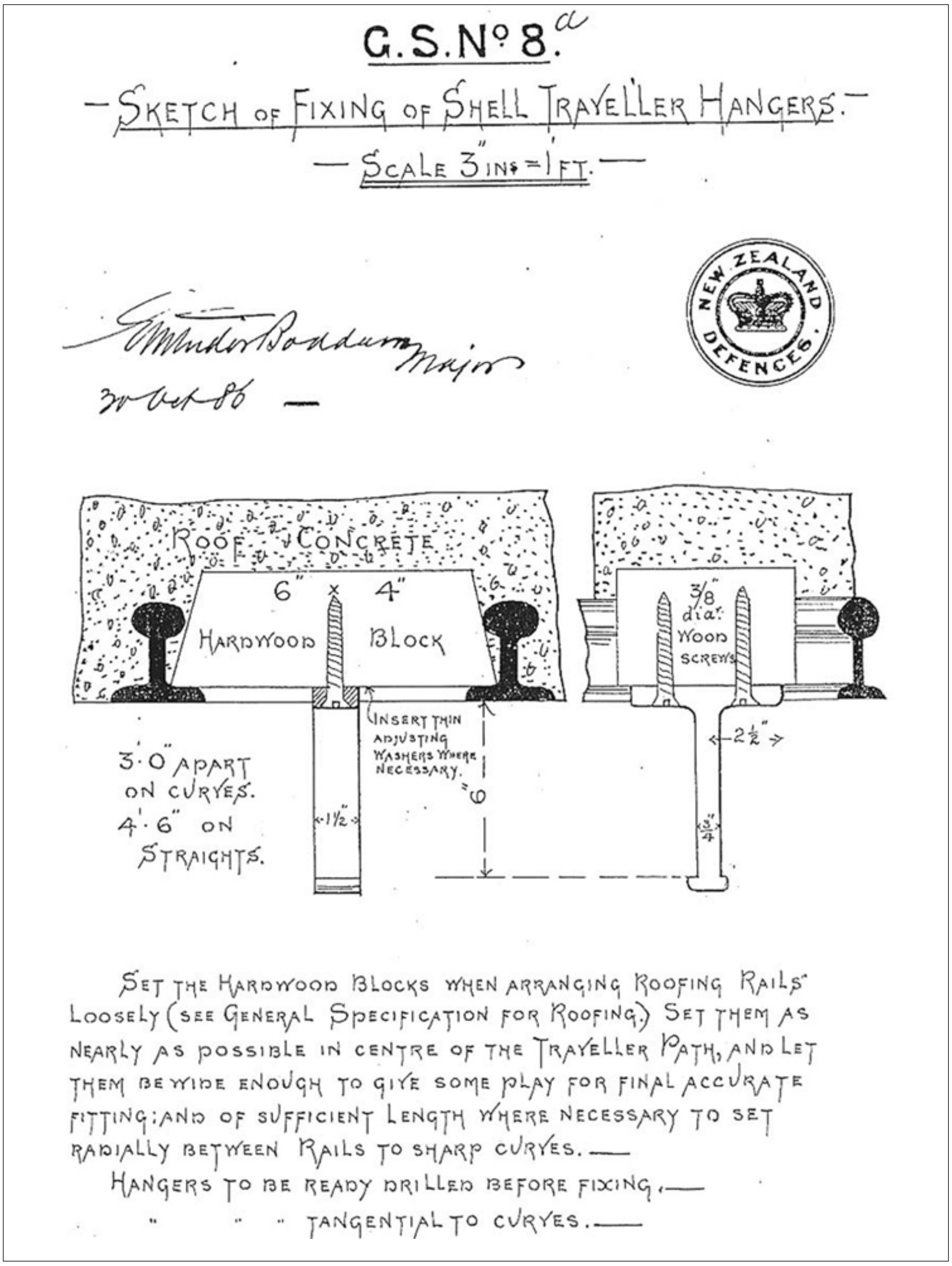
Concrete was widely used in coastal military defence structures during the Russian war scare of the 1880s. For example, Fort Takapuna (formerly Fort Caughley) has 600-mm-thick concrete retaining walls and a roof structure poured over railway irons (Figs 8 & 9). Similar designs were used in fortifications across the country.

Thornton (1996) documented the increasingly varied use of concrete in the 1890s. Mining structures such as the Crown Mine Battery at Karangahake (today an industrial monument) were built during this time, and its ruins exhibit massive concrete ramparts and impressive stone walling. Concrete also proved very useful in developing infrastructure and transport systems across the country, as in the Kohatu railway tunnel, which was built in 1893 using precast concrete blocks.

Reinforced concrete came into common use in New Zealand from the 1900s onwards, its use stimulated by the risk of earthquakes. Larger and more substantial engineering works, buildings and structures were now built of this composite material, with the increased tensile strength making it much more adaptable. Not only bridge piers but entire bridges could now be built in reinforced concrete. Reinforced concrete dams in New Zealand predate those in England, where masonry was the preferred material. Between 1904 and 1908, a dam was constructed of mass concrete in Nelson. However, this was still experimental, and it had many problems with leaking and its height had to be reduced. Ferro-concrete was also used in some of the first State houses to be built in 1905. Two of these still stand today in Patrick Street, Petone (Thornton 1996), which is now a conservation area.

Figure 7. Sacred Heart Cathedral, Wellington. Conventional stone and brick masonry, with a core of reinforced concrete.

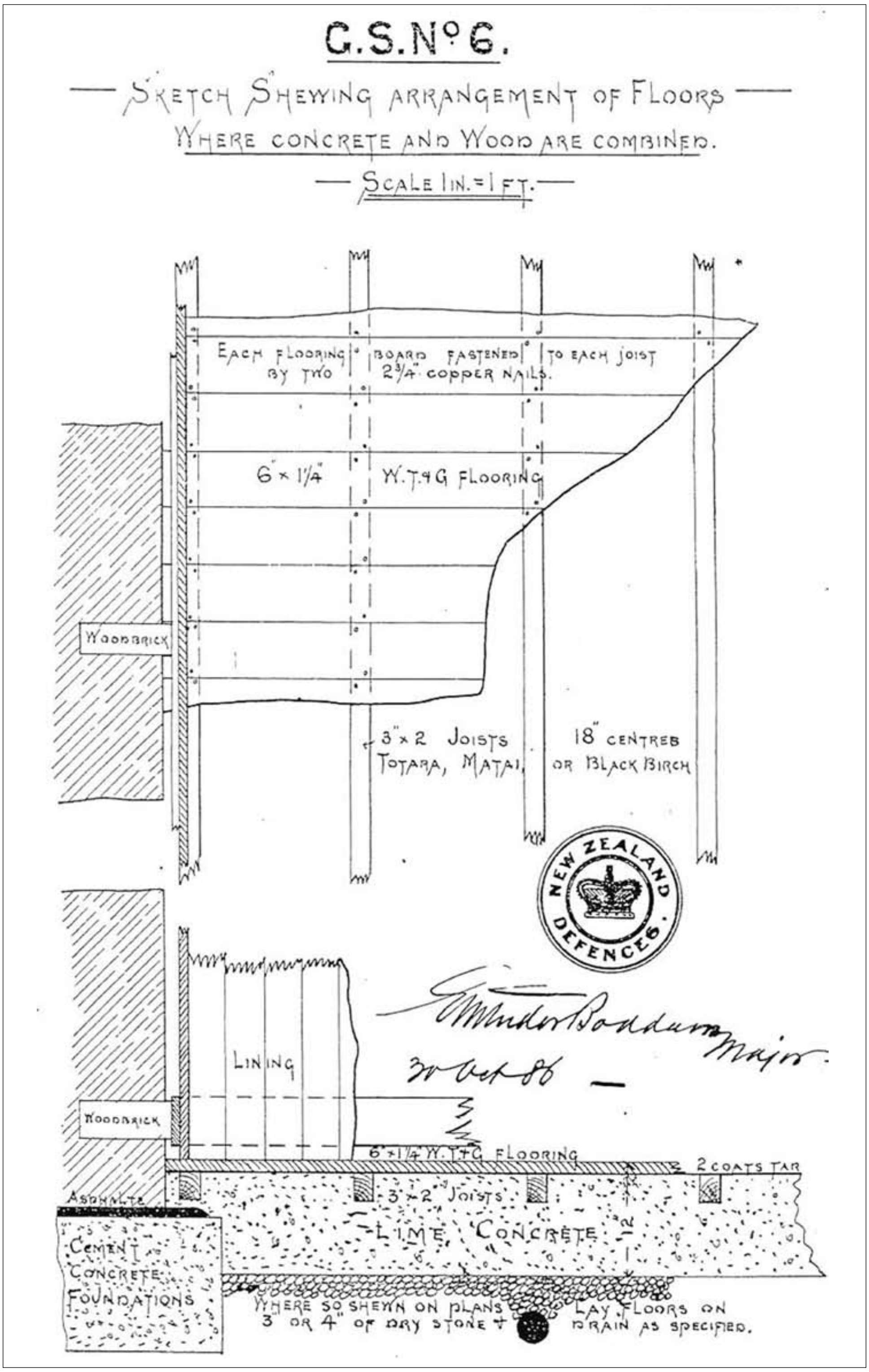
Figure 8. Detail of roof structure, Fort Cautley, Auckland (from New Zealand Defences 1890).




At the turn of the century, there was considerable debate on the merits of reinforced concrete in building, engineering and architecture journals as the building industry came to grips with its use in general construction. The Hennebique system proved to be the most popular in New Zealand. Early high-rise buildings that were built in Queen Street in the early 1900s were constructed with ferro-concrete, and this shift from two- and three-storey brick buildings to ones of six storeys had a marked impact on the appearance and form of Auckland. Examples of this new style of building include the Premier Building (1907), Security Building (1910), Warwick Building (1913–1914), Canterbury Arcade (Brunswick Building) (1914), and Whitcombe and Tombs (1916) (Schoonees 1998).

Grafton Bridge, built in Auckland in 1907, was, at the time of its construction, the largest reinforced concrete arch span in the world (Fig. 10). The

Figure 9. Detail through floor of Fort Cautley, Auckland, showing lime and cement concrete (from New Zealand Defences 1890).




first State hydro-electric generating station in New Zealand was built at Lake Coleridge in 1915, using a structure of concrete portal frames. This design set a precedent for later hydro-electric power stations.

By the 1920s, concrete technology was well established in New Zealand. Architects, engineers and contractors had by this time gained both experience and knowledge of what had become a recognised building material. Cement production was fairly standardised and suitable aggregates were generally

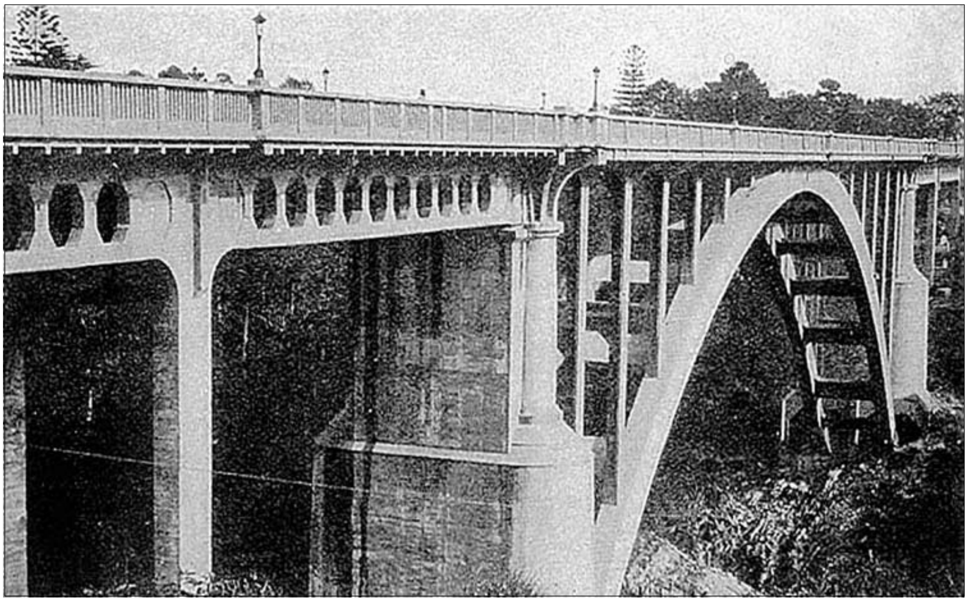


Figure 10. Grafton Bridge, Auckland, soon after it was built (from Jones 1913).

available. Concrete was now used in all types of buildings and structures. While concrete could be used in many instances where masonry would previously have been preferred, its great value lay in its structural attributes. Utilitarian structures were generally left unfinished ‘off-the-form’, but where aesthetics were a primary consideration, buildings were generally faced in stone or brick, or rendered in plaster. A notable Auckland concrete building of the 1930s was the Auckland Electric Power Board building, which was finished in a mixture of precast panels with exposed aggregate finish and cement plaster in which the colour changed subtly over the height of the façade.

## 1.3 CEMENT MANUFACTURE IN NEW ZEALAND

Nathaniel Wilson was a prominent early figure in the production of lime and cement in New Zealand. He built one of the first kilns for burning limestone on the banks of the Mahurangi River near Warkworth. With this, he produced what was called Roche lime, to which scoria ash was added, increasing the hydraulic properties of the material. The resulting cement was used for plasters and mortars. In 1878, Wilson set up a lime business with his brothers to market lime cement, and in 1880 they set about building concrete houses in Auckland using Roche lime, as well as supplying lime for general building construction in the Auckland area. A few of their houses still stand today in Grey Lynn. When the construction side of the business proved to be an indifferent success, they decided to concentrate on the production of cement and Roche lime.

In 1883, the Wilsons produced the first true Portland cement in New Zealand, with the help of a book called *Science and the Art of the Manufacture of Portland Cement* by Reid (1877). They experienced problems with kilns and burning temperatures for a few years before they produced a reliable and consistent product, which tests showed to comply with the English specification for Portland cement. They burned Mahurangi limestone, which was then ground to powder and made into bricks. These were then dried and burnt to a fusing point with coke. The resulting hard clinker was ground to a fine powder to produce Portland cement.

By the late 1890s, Portland cement manufacturing was well established in New Zealand and competing with imported cement. Wilson's Cement Company produced 1524 tons of Portland cement in 1897 and 7620 tons in 1902 (Thornton 1996). The company kept up-to-date with the latest developments in the field and installed two new rotary kilns in 1898. The cement was shipped to Auckland from a wharf on the Mahurangi River.

Smaller companies were also involved in producing lime-based cement across the country, and most districts supported enterprises that manufactured for the local market. In the South Island, the first Portland cement was produced in 1887 by James MacDonald at Pelichet Bay, Dunedin. This became the Milburn Lime and Cement Company in 1888, which later moved to Burnside in the south of the city. The company produced a cement described as 'silica Portland cement' in 1897, which was claimed to be superior to ordinary Portland cement. From 1908, the company used lime from the Makareao near Dunback, which remains their source of limestone today.

Portland cement was produced by a few other smaller companies, but none had the same success as Wilson's. The Golden Bay Cement Works began operations in 1908 at Tarakohe and later became the Golden Bay Cement Company; most of their cement was shipped to the North Island. A cement works was also started at Motupipi in 1906, and another in Picton, for which limestone was shipped from the Tata Islands. In 1895, Rutherford & Co. built a cement works on Limestone Island in Whangarei Harbour. This was taken over by Alan Hall in 1896 and became the New Zealand Portland Cement Company Ltd, which produced cement there until 1918, when the operation was moved to Portland on the other side of the harbour. In 1912, Nathaniel Wilson's son, W.J. Wilson, founded the Dominion Portland Cement Company at Portland, Whangarei Harbour, with his partner George Winstone. They ensured that they had the most up-to-date equipment and technology by visiting the USA, England, and Europe.

In 1918, Wilson's Cement Company and Hall's New Zealand Portland Cement Company amalgamated and bought out the Dominion Portland Cement Company, recognising its good site and appreciating the modern plant and equipment. The operation on Limestone Island was stopped and the Wilson Warkworth site was scaled back, producing mostly hydraulic lime and finally ceasing operations in 1929. This site of the original Wilson's Cement Works is now an interesting ruin and is open for public viewing. Similarly, Limestone Island is being preserved as a historic site and relic of this energetic industry.

Analysis of government records from 1892 (Public Works Office, Wellington 13 September 1892) showed that approximately one-third of all cement used in government works at that time was of local origin. From the turn of the century onwards, there was a gradual shift towards using local rather than imported cement, and by 1920 the great bulk of cement used was locally produced.

# 2. Concrete components and mixes

Both mass concrete and reinforced concrete are composite materials. Mass or plain concrete is made up of cement or lime, fine and coarse aggregate, and water; and reinforced concrete incorporates steel, although wrought iron was used in the earliest reinforced structures before 1900. The cement or lime is used as an adhesive to bind the coarse and fine aggregates. Water is added after dry mixing, which starts a chemical reaction with the cement or lime, resulting in a fluid mixture that hardens into a solid mass with good compressive strength but poor tensile strength. Steel reinforcing is used to improve the tensile strength of the concrete, allowing it to span considerable distances, and producing a very strong and versatile building material.

## 2.1 HYDRAULIC LIMES AND CEMENTS

Between 1841 and 1900, concrete structures in New Zealand generally made use of either hydraulic lime or natural cement (Fig. 11). From about 1860, Portland cement progressively replaced lime as the preferred active agent, initially using imported product. The proportion of Portland cement to natural cements gradually increased, so that by 1900 most concrete structures used Portland cement. After 1900, natural cements continued to be combined with Portland cement for better *workability* of mortars and plasters. Lime concrete continued to be used occasionally for non-structural elements, such as ground-floor slabs, but not for reinforced concrete.

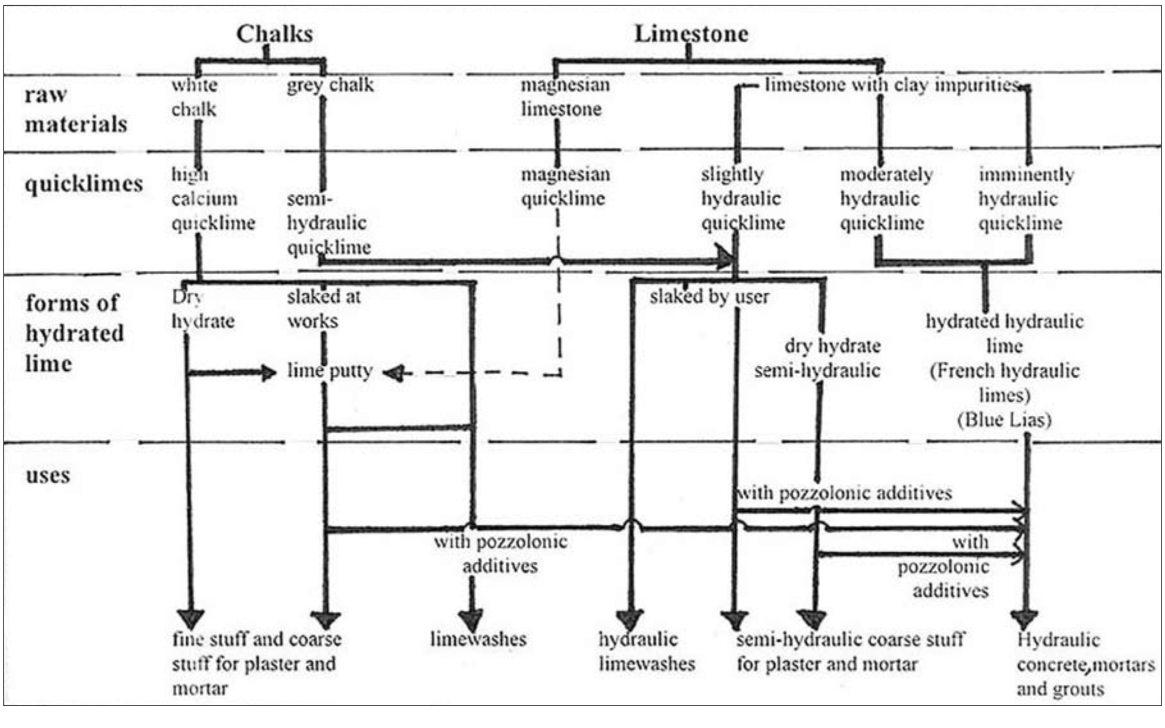



Figure 11. Types and uses of lime (from Cowper 1927).

The construction of Fort Cautley on North Head, Auckland, in 1889–1890 provides an example of the wide variety of cements used over time on one construction site (Frankham 1889, 1890). English cement and Wilson's local cement were obtained from T. & S. Morrin, and hydraulic lime was obtained from Rutherford and Co. Lime was also supplied by Carder Bros and shell lime by R. & R. Duder. The specifications suggest that both English and Wilson's cement (both early forms of Portland cement) were used for cement concrete specified for the roof and walls, while the hydraulic lime was used for lime concrete specified for the floor. The lime and shell lime were probably used for mortar and plaster, where the hydraulic properties that are necessary for concrete were not required.

To make cement, a mixture of lime and clay materials is burned. This removes carbon dioxide from the lime leaving an oxide of calcium known as '***quicklime***':

$CaCO_3$ + burning → CaO (quick lime) + $CO_2$ (carbon dioxide)

The quicklime is then hydrated, or 'slaked' (mixed with water):

CaO + $H_2O$ → $Ca(OH)_2$ (***slaked lime***)

The slaked lime is dried and ground to a fine powder.

The use of naturally occurring limestone will result in natural cement (hydraulic lime), while carefully controlled artificial mixing can be used to make artificial cements (Portland cement). When mixed with water, the powder becomes adhesive, capable of bonding fragments of stone (aggregate) into a hard mass.

Although this process has remained essentially the same since Roman times, the manufacturing process has become more sophisticated as technology has advanced. Lime and clay proportions are now precisely controlled, burning temperatures are higher, and grinding is much finer. The technical understanding of the process has increased to such an extent that recent developments in cement manufacture are redefining the nature of cement as a material. Ordinary concrete made with Portland cement generally has a compressive strength of between 20 and 50 Mpa, and a fracture energy of 120 $J/m^2$.

### 2.1.1 Natural cement

Natural cements occurred in the form of hydraulic limes[3], to which pozzolans were sometimes added. The hydraulic properties of the natural cements varied according to the type of limestone used and whether pozzolanic material was added to increase the hydraulicity. Lime concrete is both weaker and more porous than that made with Portland cement. These natural cements generally have a compressive strength of approximately one-third that of Portland cement. The fineness to which the cement was ground determined the rate and degree of ***hydration***, and also influenced the ultimate strength. Early cements were not as finely ground as modern Portland cement.

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[3] Hydraulic limes were used in the production of concrete. Non-hydraulic limes were used for mortars, plastering and lime washes.

It is most likely that the earliest imports from Britain, which occurred between 1840 and 1850, were of natural cement, as Portland cement only came into general use in Britain in about the 1860s. It is known that large quantities of Roman cement were being produced in England at this time for use by the plastering trade, but this product was not imported into New Zealand. Lime-based cements were being produced in New Zealand by the late 1860s.

Lime concrete was not generally reinforced, as it was not considered strong enough and its porosity meant that any reinforcing would be more likely to corrode: 'For reinforced concrete work cements of doubtful quality should in no case be employed, and for this reason natural cements must be avoided, as their behaviour is very uncertain, and they are more likely to be uneven in quality than artificial cements in which the ingredients can be proportioned with exactness' (Marsh 1905: 120).

### 2.1.2 Portland cement

Early Portland cements were not equivalent to today's 'ordinary Portland' cement—now more generally known as 'general purpose' cement. They were produced at lower burning temperatures and had weaker hydraulic properties, but were still stronger than natural cements. They were often lighter and greyer in colour (the natural cements tended to range from brown to light brown and paler colours). The exact specifications for Portland cement were gradually refined from its first patent in 1824 through to 1920. In 1909, C.F. Mitchell noted that 'the modern method of manufacture is rapidly superseding the old' (Mitchell 1909) and gave a specification issued by the British Engineering Standards Committee for Portland cement that had been revised in June 1907. By then, the product was substantially similar to modern general purpose cement. Further refinements of the burning and grinding processes, and research into hydration and the roles of silica and alumina led to a Portland cement that, by the 1920s, was equivalent to that used today. It is probable, therefore, that concrete structures built in New Zealand prior to 1900 contain natural cements of varying hydraulic properties. Testing and analysis will assist in determining the type and properties of cement used in a historic concrete structure.

## 2.2 AGGREGATE

The aggregate (both fine and coarse) makes up about 80% of the volume of the concrete. Shape, grading, size and type of aggregate all affect the final characteristics of the concrete produced; it is not simply an inert filler.

Before 1900, few researchers had studied the contribution made by the aggregate material to the quality of concrete. Although the importance of using clean aggregate gradually began to be understood in the 1800s, it is unlikely that the use of clean aggregates that were free of clay coatings, organic materials or sea salts was always ensured in early concrete. The consequences of using dirty aggregates include a tendency to attract and retain water, poor *setting* and *curing*, and chemical reactions that result in corrosion of the reinforcing and accumulation of *efflorescence* on the concrete surface.

In modern concrete, aggregate is carefully selected crushed stone. However, in early concrete structures, the choice of aggregate was determined largely by what was readily available. For example, in the supply of material for the construction of Fort Cautley in 1889, the aggregate was specified simply as local sand and scoria (Frankham 1889, 1890). In other examples, ceramic waste and scoria ash were incorporated in the concrete walls of a cottage in Sinton Road, Hobsonville, and the concrete walls in W.J. Wilson's house at Warkworth contained a broken brick aggregate reinforced with strained wire hawsers. It is possible that the use of such aggregates may have had an inadvertent beneficial effect by increasing the hydraulic properties of the cement and the resultant concrete. The scoria ash and burnt clay would have acted as pozzolanic materials—as the Romans discovered two millennia ago.

For many builders, economic considerations and the reality of working in a country with a rudimentary land-based transport infrastructure would have meant that the most likely sources of aggregate were those that were locally available. The most commonly used aggregates came from streams and gravel pits, and often included sea sand and shells.

Grading and size of aggregate both affect the amount of water needed to obtain workability. Generally, about 30% of the volume of well-graded sand is voids, which means that 30% of this volume of cement binder will be required. This explains the commonly used proportion of 1:3 binder-to-sand ratio often used in mortar specifications. This is a useful guideline for mixes in general, unless the historic mortar is known to have had a different binder:aggregate ratio.

There should be a continuum in the size of grains from small to large—smaller grains fill the interstices between the larger grains, keeping the amount of cement paste to a minimum. A well-graded aggregate, i.e. one with a range of particle size, improves the workability, as does using the largest possible particle size that can be compacted around and over the reinforcing. The improved workability means that less water is required and a stronger concrete is produced. This in turn limits the amount of shrinkage and deformation that takes place during drying.

The shape of the aggregate will also affect the workability of the concrete. An extremely rough, angular aggregate is less workable and may require more water to be added to the mix to increase its workability, thus reducing strength and producing a more porous concrete. Sharp aggregate can also hinder compaction. It does, however, bond well with the cement paste to produce a stronger concrete. Therefore, a balance between rounded and sharp aggregate is desirable.

Ideally, aggregate should have a compressive strength equal to that of the cement paste, should be chemically inert in water, and should be clean, hard, and free from clay coatings and organic materials to ensure a good bond with the cement. However, it is unlikely that the aggregates used in early structures would always have been ideal for the purpose. Testing and analysis, and knowledge of local history and conditions will assist in determining the most likely aggregate that would have been used in a historic structure.

## 2.3 WATER

Water is another essential ingredient in concrete. It is now understood that mixing water should be kept free from salts and other impurities: generally, if it can be drunk, it is acceptable. However, this was less well understood by the makers of early concrete, and sea water was often used when available. On occasion, salt, sugar or glycerine were added to mixing water to prevent freezing during cold weather. Some builders also adopted the practice of adding fine clay to mixing water to improve the waterproofing characteristics of the finished concrete. All of these additions would have ultimately had a detrimental effect.

In one of the standard textbooks on reinforced concrete, Charles Marsh noted that 'for ordinary concrete work sea water does not appear to have any ill effects, it is possible that the contained salts might have an injurious action on the metal' (Marsh 1905). Although he then recommended using fresh water, this indicates that at this time there was still only a vague understanding that salts might be a problem. Salts in the water have an extremely detrimental effect on reinforced concrete, and it is probable that sea water was used in many early structures.

## 2.4 OTHER COMPONENTS

Because concrete was a novel material, there was considerable experimentation to see what other materials could be added to early mixes to alter its properties. In addition to the materials mentioned above, chopped straw, earth and sticks were also sometimes included in the mix to provide additional bulk; however, these cannot be regarded as 'admixtures'. Most of these are detrimental to the concrete and reduce durability. Modern admixtures may have a role in repairs to historic concrete, and this will be discussed later (section 7.3).

## 2.5 REINFORCEMENT

Steel bars or rods embedded in the concrete act cohesively with the concrete and are placed in those parts of the structure that are likely to bear tensile or shearing forces. The reinforcing increases the tensile strength and the resistance to bending of the composite member. In beams and slabs that span from one load-bearing support to another, additional tensile strength is needed in the lower third of the concrete. For cantilevered beams and slabs, extra tensile strength is needed in the upper third of the concrete, and the reinforcing bars or rods are bent up diagonally to strengthen the concrete against shearing forces. In columns, the steel helps to resist a tendency to buckle under loads.

When reinforced concrete was first used in New Zealand in the 1870s, wrought iron was the reinforcing material. Although this has good resistance to corrosion, its tensile strength is far less than that of mild steel, with which it was replaced from the 1900s onwards, following world trends. Modern steels have higher resistance to corrosion than either wrought iron or early mild steel.

Marsh (1905) compared the use of steel and wrought iron: 'Up till comparatively recently wrought iron has been considered by most contractors as the best material for reinforcements. Steel, is however, coming more into use for this purpose, and is in some cases undoubtedly the better material to employ, but wrought iron possesses all the qualities required in most instances, and is frequently cheaper'.

In early New Zealand, experimentation was a feature of reinforced concrete construction. As in other countries, the optimum positioning of steel reinforcing in the concrete structure was not well understood at first, so reinforcing can be found in unexpected positions in early reinforced structures.

## 2.6 CONCRETE MIX

### 2.6.1 Proportioning

The ratio of water to cement is one of the most important factors governing the strength and durability of concrete. The addition of water to the cement-aggregate mix begins a complex sequence of chemical reactions in hydration, setting and *hardening*. Water in excess of that needed for cement hydration increases the porosity of the concrete and reduces its strength. Porous concrete is more vulnerable to water-soluble salts and chemical attack. This is especially a problem for reinforced concrete, as porous concrete offers poorer protection to steel, leaving it more prone to corrosion and resulting in deterioration of the concrete over time. A quite specific amount of water is necessary for hydration, and while additional water may improve workability, it actively diminishes the final strength of the concrete.

Well-compacted concrete results in a higher strength product. Thus, the optimal mix will achieve sufficient workability with the lowest possible *water:cement ratio*. The properties of the aggregates used have a large influence on workability and the amount of water needed to achieve a desired workability: there must be sufficient water to hydrate every particle of cement and cover each particle of aggregate, but not so much that when the concrete hardens, large voids previously occupied by water are left (see section 2.3). Louis Vicat identified some of these phenomena as early as the 1830s, and in 1892 Foret established that higher strengths were obtained when the mix was kept as dry as possible. However, this concept was not more widely understood until about 1915. On site, especially where mixing was done by hand, the tendency was to add more water than was absolutely necessary, to obtain a higher workability. Even in 1905, and in spite of Foret's research, Marsh gave a differing opinion as to how wet the mixture should be. He stated that both Hennebique and Cottançin, well-respected concrete designers and contractors, used fairly wet mixtures and believed that this did not reduce strength (Marsh 1905).

In 1913, Jones stated that 'there is no one formula of any value for general adaptation; and the correct proportioning ought always to be settled after experimenting with the particular coarse aggregate and sand which is to be used on the job' (Jones 1913). When specifying concrete, it has long been standard practice to require cubes of each concrete to be provided for testing. This is illustrated in the construction of Fort Cautley, where the site inspector, W. Frankham (1889, 1890), reported on the concrete tests on a regular basis.

Specifying mix proportions will not ensure that the resulting concrete has a specific strength. It is preferable to specify the type of cement and the type of appearance and finish required, and a minimum strength to be achieved after 28 days' curing. When repairing historic concretes, this will be important, and trial tests will be needed to compare the strength and properties of the repair mix with that of the original concrete that is being repaired.

### 2.6.2 Mixing

Early mixing was all done by hand. This is less efficient and produces a more variable concrete. The first mechanical concrete mixer was used as early as 1847, and by 1900 a remarkable array of concrete mixers existed. Mechanically powered mixers will have been used in New Zealand from the 1900s, but for smaller structures and those on remote sites, hand mixing was more common. By 1905, machine mixing was advocated for all larger projects internationally, to obtain more uniform concrete, and this would also have been the case in New Zealand (Marsh 1905). The first 'ready mixed' concrete was used in the USA in 1926. Today this is an almost universal practice, and most concrete is brought to the site pre-mixed to very precise specifications.

# 3. Properties of concrete

Concrete is essentially a manufactured material. As mentioned above, its properties are complex and varied, and are determined not only by the component materials, but also by the manufacturing process of the cement, the design of the structure and the construction procedures followed on site. Today, materials, workmanship and the design of concrete structures are much more standardised than they were in the past. Concrete that has been prepared properly and placed in a well-designed building is a very durable material with a slow rate of deterioration. However, this was very often far from the case in historic structures.

The properties of early concrete structures may vary considerably from each other and from modern, general purpose cement reinforced concrete. The behaviour of such structures must, therefore, be individually assessed according to the materials used, and their design and detailing.

Mass or plain concrete, which was produced with hydraulic lime, natural cement or early Portland cement, is an essentially different material from modern reinforced concrete. Each mix has differing strengths and weaknesses, and is exposed to different deterioration processes. Concrete without steel or iron does not have the problems associated with corrosion and exponential deterioration due to rusting steel that reinforced concrete has, but it is far more vulnerable to seismic and tensile forces than reinforced concrete.

## 3.1 NATURAL ALKALINITY OF CONCRETE

The pH of concrete is significantly affected by the hydration of cement, as one of the by-products of the hydration reaction is calcium hydroxide, which is highly alkaline. The presence of a high pH ($> 12.5$) produces a passive film on the surface of embedded reinforcing steel, and a reserve of calcium hydroxide serves as a buffer to prevent the pH from dropping. Thus, although high moisture levels may be present in highly alkaline concrete, the embedded steel does not corrode. This film remains intact as long as the concrete surrounding the bar remains highly alkaline and is not contaminated with salt. Acidic substances have a low pH and attack highly alkaline concrete, reducing its pH.

The presence of calcium hydroxide may be reduced by the presence of *free water* passing through the concrete and/or by the effects of *carbonation*, in which atmospheric carbon dioxide penetrates the concrete through its capillary pores, and reacts with and removes the calcium hydroxide. Thus, there is a loss of protection to the steel where reinforcement is in contact with carbonated concrete.

## 3.2 STRENGTH

Concrete was initially used as a replacement for or component of masonry because of its adhesion to other materials and good compressive strength. The achievable compressive strength increased as the understanding of cement materials and their hydraulic properties improved. Portland cement concrete rapidly became the predominant material used for engineering and building, due to its compressive strength being approximately three times that of concretes based on hydraulic lime or natural cement. A range of factors affect the ultimate strength of concrete, including the water:cement ratio, compaction, the aggregates used and workmanship (see section 2). General purpose cement concrete usually has an average compressive strength of about 25 MPa, while that of lime concrete could range from about 5 to 10 MPa (Mitchell 1909).

As mentioned above, plain concrete was mostly used for its compressive strength, as this was about ten times its tensile strength. The addition of steel reinforcing from the 1900s resulted in a material with combined compressive and tensile strengths, which made it extremely versatile (Fig. 12).

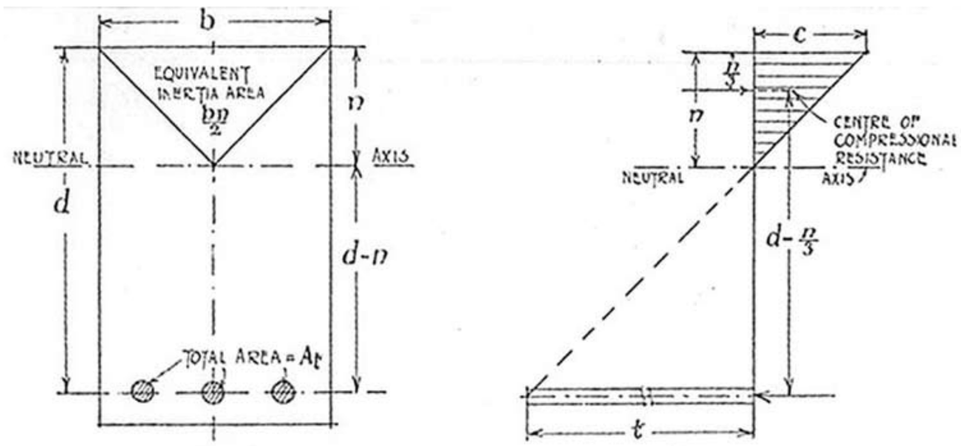



Figure 12. How a single reinforced beam resists compression and tension (from Jones 1913).

## 3.3 MOVEMENT

Concrete shrinks when drying (*drying shrinkage*). A proportion of this initial shrinkage is irreversible, but even fully cured concrete expands when wetted and shrinks as it hardens. Similarly, like most other materials, concrete expands and contracts with changes in temperature. If the movement exceeds the tensile strength of restrained concrete, it will crack. The likelihood of moisture movement increases with the ratio between water and cement, and between cement and aggregate.

'Carbonation shrinkage' can also occur, where high levels of carbon dioxide from the atmosphere react with the hydrated cement paste. The extent of this shrinkage can be equivalent to that of wetting-drying shrinkage.

Creep is the deformation caused by a constant load. In concrete, there is a gradual increase of deformation due to the first application of a load. Initial creep is rapid at first but approaches a limit after about 5 years. The creep is roughly in proportion to the load, and is greater in weaker and less mature concrete.

## 3.4 PERMEABILITY

All concrete is to some extent permeable, particularly to water vapour. Lime concrete, however, is much more permeable than modern, general purpose cement concrete. Well-compacted concrete made with a low water:cement ratio has good resistance to water absorption, but where more water has been used in the mixing, as was often the case in early concrete, the concrete tends to be more porous, and hence more permeable. This characteristic is more pronounced where lime cements and early Portland cements were used. Conversely, poorly compacted or 'bony' concrete may also be porous because of voids between aggregate particles that were not filled with cement paste.

The permeability of early concrete can be a disadvantage where reinforcing was incorporated, as this reinforcing is more likely to corrode. In non-reinforced concrete structures, however, permeability is not necessarily detrimental, although the moist concrete may more readily support organic growths. Lime concrete has a greater ability to absorb and lose water vapour than general purpose cement. Condensation can be a problem with solid concrete walls, so the ability to 'breathe' can be an advantage (see section 7).

## 3.5 DURABILITY

Many circumstantial external factors will affect the durability of any concrete. The specific effect of these on an individual structure will depend on the nature of the particular concrete and the intensity of the external agent. External factors include frost, chemicals and fire.

### 3.5.1 Frost

Concrete can be damaged by the expansion of ice crystals, which are most likely to occur where water has lodged in pores or cracks in the concrete. A dense concrete will have a high resistance to this type of erosion. In contrast, concrete with voids, cracks or large pores will be more vulnerable to frost damage and, if reinforced, corrosion of the steel will be more likely.

### 3.5.2 Chemicals

As a general principle, the better the compressive strength, the better the chemical resistance. Lime concrete, which is softer and weaker than Portland concrete, is more vulnerable to chemical attack. In concrete that has voids and cracks or is porous, reinforcing steel will be more likely to be affected by chemicals, and this may result in corrosion damage to the structure.

### 3.5.3 Fire

Reinforced concrete is one of the most fire-resistant of common structural materials. However, although the strength of ordinary concrete increases up to temperatures of 120°C, there is a serious loss of strength at higher temperatures. Flexural strength is more affected than compressive strength because of the effect of heat on steel reinforcing. The fire resistance of non-reinforced concrete is slightly lower than that of brick of the same thickness, although the type of aggregate will affect this. Siliceous aggregates have the poorest fire resistance, while those that include burnt clay products, pumice, well-burnt clinker, crushed limestone and pelleted fly ash have greater fire resistance.

Concrete fails in fire because of the differential expansion of the hot exposed layers over cooler internal layers. The insulation that the concrete provides is an important factor in its fire resistance, and lightweight aggregate concrete performs better in this respect. If steel reinforcing is exposed, fire resistance and structural strength reduce dramatically as the rapid conduction of heat increases the temperature differential.

One of the more destructive forces in a fire is the spontaneous expansion of water into steam, and this may be enough to shatter concrete members, especially older concretes with a high content of free lime.

## 3.6 APPEARANCE

Early concrete structures were often rendered with plaster or clad in a veneer of brick or stone. Where the surface was left untouched after the formwork was removed, the aesthetic effect depended on the inherent colour and texture of the concrete, and the quality of the formwork and workmanship.

The final colour of concrete depends on the colour of the cement as well as that of the aggregate; for example, where scoria was used for aggregate, the colour of the concrete tended to have a reddish tinge. Early Portland cements were generally lighter in colour than modern grey, general purpose cement. However, all concrete changes appearance over time, as the initial cement 'laitance' (milkiness, i.e. fine particles in the surface) weathers away from the aggregates at the surface. As the aggregates are revealed, there may be quite dramatic changes in the appearance of the concrete.

# 4. Causes of defects and deterioration in historic concrete

Identification of the cause of concrete deterioration in historic buildings is seldom straightforward. Historic concrete structures present some deterioration problems that are not found in modern concrete structures, due to the characteristics of their design and construction. Deterioration is also usually the result of several interrelated causes, making identification of the exact causes difficult; for example, a single section of historic concrete could be cracked, spalled and on the verge of structural collapse as a result of a whole range of possible causes.

The problems that arise in mass or plain concrete structures differ from those of early reinforced concrete structures, and deterioration in the latter is often exacerbated by corrosion of the reinforcing.

When determining the cause of defects and deterioration in a historic concrete structure, there are three main factors to consider:

- The type of concrete and its properties (materials used)
- The method of placement of the concrete (workmanship)
- The environment to which the concrete is exposed (environmental effects)

## 4.1 MATERIALS USED

For a concrete structure to be durable, it is important that its component materials are fully compatible with all the conditions it may encounter during its anticipated life. However, this was not always the case in early concrete (see section 2). In the past, inappropriate or poor quality materials may have been used to make concrete because knowledge of concrete chemistry at the time was inadequate. Occasionally, these materials can be detected very quickly, but their effect is usually long term, and they can affect the properties of the concrete and its ability to withstand other agents of deterioration. The following sections outline some of the factors that need to be considered.

### 4.1.1 Cement

Early concrete may have been produced using a number of possible types of cements, ranging from hydraulic lime cements, with or without pozzolans added, to early Portland cements, which were not yet the same as modern general purpose cement.

Concrete made with natural cement or hydraulic lime was usually lighter and more rapid-setting than that made with Portland cement and had an ultimate strength of approximately one-third or less of modern general purpose cement. While the weakness and higher porosity of lime concrete generally means that this was not suitable for reinforced concrete, careful production and supplementary pozzolans may have resulted in a concrete with a strength and porosity that matched that of early Portland cement concrete.

Although all cements produce a concrete that contains some excess free lime, this was more common in the early cements. Excess free lime is soluble in soft water and can be leached out of the concrete. Leaching is more likely in porous or finely cracked areas exposed to excessive and continual moisture movement, and its loss may lead to loss of strength and gradual disintegration of the material. On the other hand, continual and gradual hydration in concrete with less finely ground cement can result in it still reaching its full strength potential 30 years later.

### 4.1.2 Water

Concrete must be mixed with clean water that is free of salts, oil, clay and organic matter. The harmful effects of sulphates (found in very hard water) and chlorides (found in sea water) in concrete mix water were not understood until after 1900, and it is possible that historic concrete, particularly on coastal sites, will contain these impurities. The presence of chlorides in mix water may result in a reduction of the ultimate strength of the concrete and of the effectiveness with which it naturally inhibits the corrosion of ferrous reinforcement (see section 4.3.3).

An increased water:cement ratio reduces the ultimate strength of the concrete and makes a more porous concrete (Fig. 13).

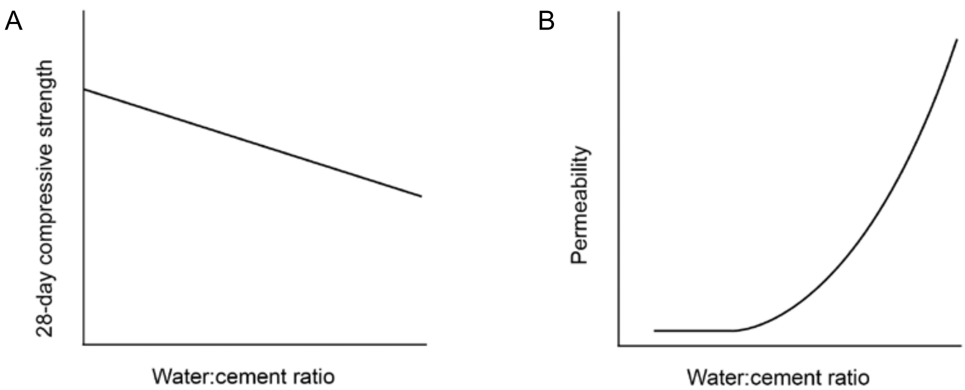



Figure 13. Effect of water:cement ratio on A. concrete strength and B. permeability.

### 4.1.3 Aggregates

Concrete containing aggregates that expand and contract differently from the cement paste during changes in temperature, will experience internal stresses. In addition, the use of unwashed aggregate will result in a poor cement-to-aggregate bond. Thus, separation along the cement-aggregate interface is likely.

Porous aggregates are more susceptible to freeze-thaw cycles, and the absorption of moisture and subsequent freezing may result in internal pressures that will damage the concrete.

Some aggregates contain minerals that react chemically with cement, producing reaction by-products that have a greater volume than the original materials. This can also cause internal bursting pressure (see section 4.3.3). This becomes evident on the surface, with the appearance of a maze of pattern cracks that precede disintegration.

### 4.1.4 Reinforcing

Concrete used before 1900 was often not reinforced but may have had organic 'binders' such as chopped straw, shavings, manure or leaves added in an attempt to provide some tying effect. These substances provide built-in planes of weakness in the concrete and also act as wicks, transporting moisture into the mass.

Wrought iron bars in early reinforced concrete were moderately corrosion-resistant. However, this may be offset by the likelihood that the concrete will have been more porous, resulting in the reinforcement being more exposed to moisture and chlorides than in later concrete. Where wrought iron is subject to corrosion, the resultant high volumetric expansion is likely to be very damaging to the structure.

Older structures also often fail to provide sufficient cover of concrete to the reinforcing steel, resulting in the early onset of corrosion. Modern practice requires at least 50 mm cover to reinforcing steel.

### 4.1.5 Additives

In addition to the organic matter mentioned above, additives were sometimes added to concrete. Clay was occasionally added in an attempt to make the concrete impermeable. However, this had the contrary effect of absorbing moisture and reducing the ultimate strength by crumbling within the cement paste. Salt was sometimes used to prevent freezing in cold conditions, but this is highly detrimental to reinforcing. More recently, calcium chloride was used to accelerate the setting and curing process, but this is now strongly discouraged due to its corrosive effect on reinforcing.

## 4.2 WORKMANSHIP

The properties of concrete are determined not only by its component materials but also by the design of the structure and the construction procedures followed on site. Historically, quality control and supervision varied enormously within the confines of available knowledge. Several aspects of historic concrete construction technology and design contribute directly or indirectly to concrete deterioration, as outlined below.

### 4.2.1 Batching and mixing

The common historic practice of hand mixing concrete produced a less even and less consistent concrete. In addition, variations in the mix proportions of adjacent pours may have resulted in differential expansion and contraction, and thus cracking. Lack of knowledge about the optimum water:cement ratio may have resulted in excessive water being used in the mix to improve its workability, resulting in a more porous material with lower ultimate strength and increased risk of *segregation* of cement. Such concrete is more vulnerable to the effects of moisture, chlorides or carbonation, and ultimately, structural failure.

Shrinkage cracks are common in historic concrete structures because of incorrect proportions of the component materials. Where the mix contained a high cement content, significant initial shrinkage may have taken place, resulting in early permanent cracking. If restrained or concentrated, the stresses caused by drying shrinkage may have caused cracking in long walls and roof slabs. Shrinkage cracks are generally long and regularly spaced and occur especially at a change of cross-sectional thickness or from the corners of an opening in the concrete. One of the roles of reinforcement is to distribute the stresses of shrinkage. Thus, in reinforced concrete such cracks tend to be more frequent but closed, whereas an unreinforced wall may have fewer cracks, but these will probably be wider.

### 4.2.2 Shuttering and formwork

The quality of the formwork has a marked impact on the resultant concrete (Fig. 14). In the early production of concrete, the design and detailing of formwork was still developing. Inadequately designed formwork and poor workmanship often allowed bulging of the surface and leaking from the form, resulting in areas of lower water:cement ratio and *honeycombing* of the surface.

The concrete structure could also have been physically damaged if poorly designed formwork was removed, especially if removed before the structure had reached adequate strength.

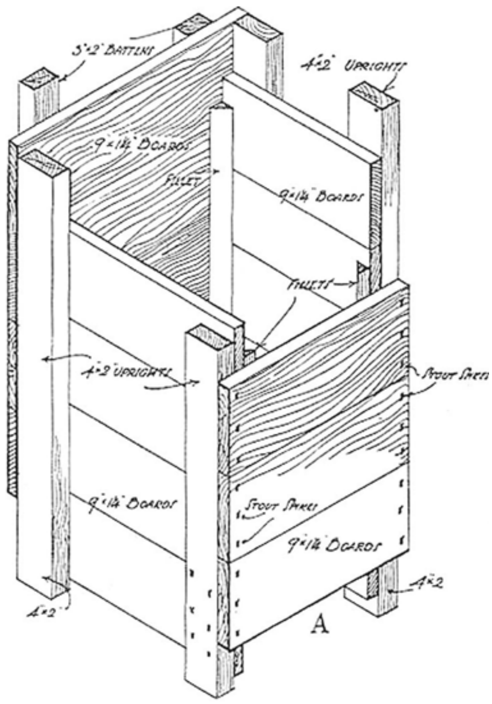



Figure 14. Typical column form with spiked-on front boards (from Jones 1913).

### 4.2.3 Transportation and placement

The dropping of concrete into the forms from a high level may have caused segregation of aggregate from the cement matrix, and air pockets beneath the reinforcement. This problem was not understood in early concrete; in fact the practice was advocated in some early texts as a way of strengthening the concrete (Gwilt 1881).

The addition of rocks (or plums as they were called), which were pressed into the concrete already in the forms, resulted in a poor bond with the cement paste and thus planes of weakness in the material. This practice was sometimes carried out in early concrete to increase the volume of the concrete mix.

Excessive *ramming*, tamping, *vibrating* or finishing will have caused water, cement and fine aggregates to accumulate at the top of the pour, and this may be followed by later delamination of this cement-rich layer, which is weaker than the bulk of the material below. Similarly, the practice of shovelling aggregate back from the forms, or tapping and vibrating formwork, will have caused concrete to set with a dense cement-rich skin at the form face. Water migrating from a fresh pour of concrete to an adjacent pour that has set and dried can cause a localised area of low water:cement ratio and honeycombing.

### 4.2.4 Climate during construction

Knowledge of the effects of weather on concrete was less well understood during early use of the material. Exposure to temperature extremes during the curing process affects the strength of the bond achieved between particles of cement, and between cement and aggregate. This decreases the ultimate strength of the concrete and reduces its ability to resist the effects of other agents of deterioration. The degree of damage depends on the severity of the conditions or the rapidity of drying.

It is not possible to identify the effects of weather in historic concrete from casual observation, so laboratory analysis or microscopic examination may be necessary. However, if concrete was exposed to severe conditions of freezing, high temperatures or rapid drying during curing, it is unlikely to have survived long enough to become historic.

### 4.2.5 Curing

The importance of allowing sufficient time for adequate curing of concrete was not initially understood. Until this had been determined, it is probable that curing times for early concrete structures were often inadequate, resulting in the concrete drying too rapidly, leading to drying shrinkage and cracking.

### 4.2.6 Detailing

Although 19th century builders and engineers had a good understanding of the importance of sound detailing, its importance for colonial concrete structures may not always have been appreciated. The tendency of fluid concrete to lie flat in the formwork reduced the likelihood of water running off the resultant horizontal surfaces. Unless such exposed surfaces were later plastered, water would continue to lie here, increasing absorption by the material.

The concrete cover over reinforcing was often not sufficient to protect it from corrosion even up to the 1950s, as the impact of corrosion of the reinforcing and how to prevent it was not yet fully understood. Furthermore, unprotected iron or steel fittings cast into the surface of concrete were vulnerable to corrosion; this will have caused rust staining of the concrete surface and may have exacerbated corrosion of reinforcing steel.

Early makers of concrete did not recognise the need to allow for movement of concrete that would result from changes in moisture content and external temperatures. Thus, there was a lack of expansion joints, which can result in compressive stress in the structure. The need to prepare junctions between different concrete pores before pouring was also not well understood at first, resulting in planes of weakness in the structure at these points and a point of entry for water.

## 4.3 EFFECTS OF THE ENVIRONMENT

The inherent weaknesses of many early concrete structures have been exacerbated by hostile environments. This affects both reinforced and unreinforced early concrete, although plain and mass concrete do not have the additional problems related to corrosion of reinforcing.

### 4.3.1 Environmental causes of stress in concrete

Concrete is generally more vulnerable to tensile and shear stresses than to compressive stress. Where internal or external forces exceed the strength of the concrete, cracking will occur in tension or shear, and crumbling in compression. Some of the causes of this are outlined below.

***Seismic movement***

Many parts of New Zealand are seismically active. While both mass concrete and reinforced concrete will be affected by seismic movement, mass concrete is more vulnerable, and will be more likely to suffer serious cracking and structural damage as a result. Well-designed reinforced concrete will be better able to withstand seismic movement because of its inherent tensile strength.

### *Movement due to absorption and loss of moisture*

Concrete expands as its moisture content increases and contracts as it decreases. Although this movement is never equal to total drying shrinkage, the amounts can range from 0.01% to 0.5%, depending on the concrete. If restrained, this stress can cause cracking. Absorption expansion and contraction are most significant in conditions approaching saturation (e.g. marine piles at the high water mark).

### *Thermal expansion and contraction*

Like most other structural materials, concrete expands when heated and contracts when cooled. If this change in volume is restrained, the resulting stress can cause the concrete section to crack. Temperature cracks are common in early concrete.

Cracking is most likely:

- In floor slabs or retaining walls that have no expansion joints
- At the intersection of two adjacent concrete surfaces
- Where a change in the dimensions of the concrete section causes differential expansion and contraction between the two elements
- Where concretes of slightly varying densities meet with a *cold joint*

### *Freeze-thaw cycles*

The formation of ice crystals in pores and cracks can cause expansive forces, which cause cracking or widening of existing cracks. This is more likely to occur in concrete that was made with a high water:cement ratio.

### *Loading*

Concrete designed to carry a load will undergo creep (see section 3.3). If the load exceeds the design capabilities of the structure and the forces are greater than the structure's tensile or shear strength, structural cracks or even failure may occur. Depending on their current use, early concrete structures may be required to carry loads greater than they were originally designed for. If loads have changed significantly, their strength in relation to their use needs to be assessed.

## 4.3.2 Corrosion of reinforcement and metal fittings

Well-made concrete provides an ideal environment for the protection of iron or steel from corrosion despite the presence of oxygen and water. Not only is concrete relatively inert, but its high alkalinity (pH 13) passivates the steel by forming a protective iron oxide film (ferrous hydroxide) over it. As long as this protective layer is maintained, the steel will not corrode.

There are, however, several reasons why the protection provided by the concrete may fail. This may be due to the nature of the concrete itself (e.g. it may be porous), or factors affecting it (e.g. it may experience movement and cracking, exposing the reinforcing to moisture, chlorides or carbonation, all of which accelerate corrosion). Deterioration of the concrete will cause further corrosion of the reinforcing, which in turn will accelerate deterioration of the concrete; the pressure exerted by corroding metal fittings, such as railing posts, hardware and lintels, can be sufficient to burst surrounding concrete.

Damage due to reinforcement corrosion is characterised by surface cracks running parallel to the direction of reinforcement. As this condition deteriorates, the surface concrete spalls from the reinforcement, starting at the mid-diameter of the bar. Surface rust stains usually accompany reinforcement corrosion, and sometimes the stains appear on the surface before any physical evidence of damage is apparent.

Although the understanding of concrete as a material was increasing by the time reinforcing was introduced, the causes and effects of corrosion of reinforcing were not appreciated for many years. The key environmental factors that contribute to this corrosion are moisture and oxygen, which react with exposed unprotected metal, chloride attack (extremely common in New Zealand), and carbonation (less common in New Zealand as it arises principally from exposure to industrial and urban pollution).

### *Moisture and oxygen*

If reinforcement or externally mounted metal fittings are exposed to moisture and oxygen as a result of a defect in the surrounding concrete, the metal will begin to corrode. This produces oxides that occupy approximately eight times the volume of the parent metal. The resulting stresses will first crack and then spall the adjacent concrete. This corrosion is exacerbated and accelerated by chlorides and carbonation.

### *Chlorides*

Chloride ions are the most common reason for corrosion of reinforcement and deterioration of concrete in New Zealand. The presence of free chloride ions within the pore structure of concrete interferes with the passive protective film of ferrous hydroxide that naturally forms on reinforcing steel. They 'de-passivate' or break down this protective coating, allowing the corrosion process to begin (Fig. 15).

Chlorides enter the concrete through the outer surface and are variable in nature. They can be introduced from contact with saline ground water, sea sprays and mists, solutions containing de-icing salts, mixing water that is contaminated with chloride, or from the admixture of calcium chloride.

Chloride ions exist in two forms in concrete:

- Free chloride ions, which are mainly found in the capillary pore water
- Combined chloride ions, which result from the reaction between chloride and the cement hydration process

The corrosive effect of chloride is significantly influenced by the presence of free chlorides. The proportion of these two forms depends upon when the chloride entered the concrete. For example, if chloride was introduced as calcium chloride at mixing, approximately 90% may form harmless complexes leaving only 10% as free chloride ions. If, however, sea water penetrated the surface of the concrete, the ratio of free to combined chloride ions may be 50:50.

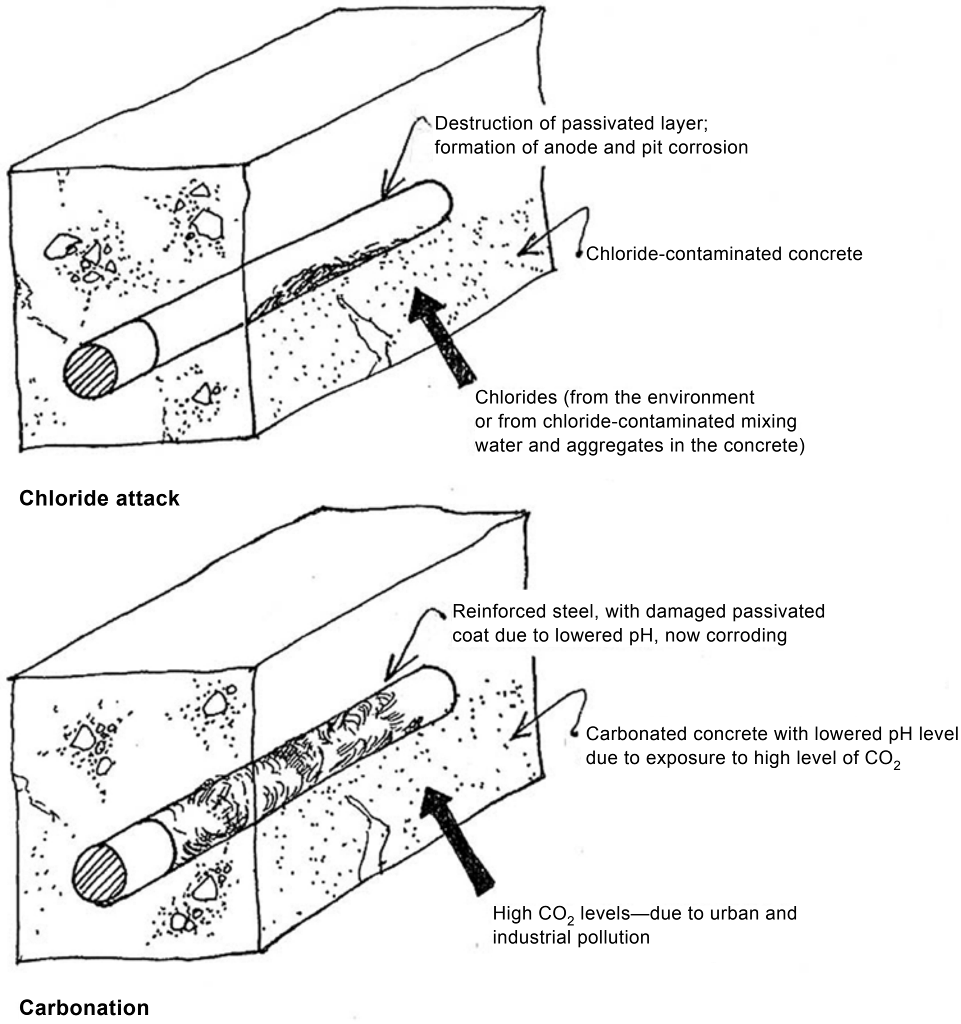



Figure 15. Corrosion of reinforcing by chloride attack and carbonation.

There is no single acceptable level for chloride content. Instead, the effects of chloride are classified in terms of risk of corrosion because, in certain conditions, even low levels of chlorides may pose some risk. The risk of corrosion due to chlorides in the concrete is assessed according to the amount of chloride measured as a percentage of the weight of the concrete. Where this is found to exceed 0.15% of the weight, the risk is considered high, while below 0.05% the risk is low. The overall effect of reinforcement corrosion caused by chlorides must be considered in association with the depth of reinforcement and the depth of carbonation.

Chloride-induced attack of reinforcement may occur even in apparently benign conditions where the concrete quality appears to be satisfactory. If the supply of oxygen is poor, reinforcement corrosion may still take place. Chloride-induced corrosion results in localised breakdown of the passive film rather than the widespread deterioration that occurs with carbonation. The localised electrolytic cells that are formed cause rapid corrosion of the metal at the anode, leading to the formation of a ‘pit’ in the bar surface and significant loss in cross-sectional area. This is known as ‘pitting corrosion’, and occasionally a bar may be completely eaten through. Failure of reinforcement may, therefore, occur without any visual sign of cracking or *spalling*.

All aggregates that are commonly used for concrete mixing contain a background level of chlorides—usually less than 0.06% by weight of cement. In the 19th century, calcium chloride was used as an accelerating additive at the time of mixing; this also became popular again during the 1950s and 1960s. The presence of calcium chloride cast within the mix usually gives a chloride level that is significantly greater than 0.4% by weight of cement.

The effects of calcium chloride within the mix are further exaggerated by the presence of deep carbonation, which releases free chloride ions into solution, increasing the likelihood of corrosion. For this reason, problems with many older structures and properties may only have become evident several decades after their construction, as carbonation mobilised chloride ions within the concrete pore structure.

There is a high likelihood of finding chloride in historic concrete in New Zealand. Early concrete practices used sea water for mixing and calcium chloride to accelerate the curing process—a practice now strongly discouraged. The porous character of much early concrete meant that there will have been a high diffusion rate of chlorides, so that reinforcing was more vulnerable to chloride from external sources than modern-day concrete.

### *Carbonation*

Carbonation-induced corrosion is perhaps the most common form of reinforcement corrosion. Its effects are usually readily visible and its subsequent repair is easier than for =chloride-induced corrosion defects.

Carbon dioxide and sulphur dioxide react with cement to form calcium carbonates. This process is called carbonation and leads to a reduction in the pH of the concrete, making the reinforcing more susceptible to corrosion: at $pH < 10$, the steel loses its passivation and corrodes in the presence of water and oxygen. Carbonation is more likely to occur in concrete with low cement content or high water content, or where poor compaction has resulted in a porous concrete. It is also more likely to occur in urbanised and industrial areas.

In mass concrete, carbonation may cause some shrinkage if the concrete is porous and may exacerbate cracking. The reaction also causes the formation of a thin skin on the concrete that is denser and less permeable than the mass of concrete beneath. Under the effects of weather and temperature fluctuations, the differences in the physical properties of this skin and the underlayer give rise to crazing of the surface. Carbonation combined with the freeze-thaw cycle can result in the skin detaching from the mass of concrete as a spall. This skin can be between 5 mm and 25 mm deep, depending on the porosity and age of the concrete. The rate of carbonation depends upon the quality of the concrete and its porosity: the higher the porosity, the higher the rate of carbonation. It is also a function of time:

$$D = KT^2$$

where D = depth of carbonation, K = carbonation coefficient and T = time of exposure to carbon dioxide.

In reinforced concrete, carbonation has an even greater effect, especially where there is insufficient concrete cover over the reinforcing steel. When the depth of carbonation reaches the reinforcing steel, the natural alkalinity of the concrete is lost and the concrete is no longer protected against corrosion. This is known as the initial stage. Corrosion begins at the propagation stage, for which both water and oxygen are required. An electrochemical mechanism occurs that involves the formation of a corrosion cell with an anode and a cathode, and the electrolytic solution of ions within the concrete structure. This causes electrons to flow through the steel from the anode to the cathode, which releases metal ions into the solution at the anode, resulting in a loss of reinforcement cross-section. Corrosion cells occur very close together to form uniform corrosion over the whole of the steel surface. Initially, insoluble iron oxide (rust) is formed on the surface of the bar, which occupies a larger volume than that of the iron, thus producing expansion forces that crack and spall the covering concrete. The rate of corrosion is mainly affected by the rate of oxygen transfer to the cathode in the presence of moisture.

Although both air and moisture are required for reinforcement corrosion, in dry (internal) environments it is typical for the depth of carbonation to exceed that in comparable external concrete members. This is because the pore structure within external concrete is subject to alternate wetting and drying, which effectively blocks the pore structure for much of the time, thus reducing the rate of carbonation.

Carbonation does not have a deleterious effect on concrete itself—on the contrary, its effect is to locally increase the strength of the concrete within the cover zone.

### 4.3.3 Chemical attack

Most forms of chemical deterioration encountered in historic concrete are external, because internal chemical reactions usually begin soon after mixing. In addition to carbonation (section 4.3.2), there are several forms of chemical attack that may be encountered, some of which are outlined below.

#### *Acids*

Concrete is alkaline and thus susceptible to chemical attack by acids. The usual sources are acidic rainwater in industrial areas, acidic soils and groundwater, and acidic runoff from plants, particularly mosses and lichens, growing on or near the concrete.

When acids react with the cement, the *reaction products* form a solution with water that etches the concrete surface. These effects can be readily identified, as they often trace the pattern of water runoff over the surface. Deterioration begins with loss of the fine aggregates, and continues until coarser aggregate is left protruding from the cement matrix. This will then eventually lose its support if the acidic runoff is strong and continuous. The resulting porous and pitted concrete surface is more vulnerable to other forms of deterioration.

### *Alkali-aggregate reaction*

Concrete can deteriorate as a result of an interaction between alkaline pore water and reacted minerals in certain types of aggregate. This mechanism of deterioration is generically known as alkali-aggregate reaction (AAR) or, in its most common form, alkali-silica reaction (ASR).

ASR was first identified as a problem in the early 1970s. It involves interactions between hydroxyl ions of sodium or potassium alkalis in pore water and the siliceous minerals in some aggregates. Certain geographical regions are more likely to be a source of aggregates known to contain high levels of silica and the effect is more likely to occur in structures constantly exposed to weather.

The products of these reactions form a 'gel' in the pores. This 'gel' attracts water, resulting in a volume expansion that causes disruption and ultimate cracking of the concrete. Over time, the reaction gel may be dissolved or leached away, leaving only a pattern of cracking caused by the original reaction stresses.

The main external evidence of deterioration of concrete due to ASR is cracking. In unrestrained concrete, the cracks have a characteristic random distribution, often referred to as 'map cracking'. Where the expansive forces are restrained by reinforcement, the pattern of cracking will be modified, with cracks tending to run parallel to the main reinforcing bars. Advanced stages of ASR may be identified by the presence of gel emanating from structural cracks as soft, whitish, rubbery deposits on the surface of the concrete, which eventually dry to become hard and brittle. Laboratory testing of dust samples may give an indication of the likely presence of a high concentration of alkalis and/or silica. However, the only certain evidence of ASR is provided by petrographic examination of thin slides prepared from cored samples.

The development of ASR is a slow process and cracking may be visible on the surface before substantial loss of comprehensive strength has occurred. Expansive pressures may cause bowing and movement of concrete components. The long-term durability of components in terms of frost action and reinforcement corrosion may be affected by associated cracking.

At present, concrete affected by ASR is considered to be non-repairable. In the early stages, deterioration may, however, be restricted by waterproofing and repair works to restrict the passage of moisture into the concrete.

### *Sulphate attack*

Concrete is susceptible to attack by sulphates, which are found in soil, aggregates, groundwater, gypsum plaster, flue gases and clay bricks (particularly those fired at low temperatures). Sulphates react chemically with tri-calcium aluminate (a constituent of both Portland cement and hydraulic lime) to produce a greater volume of reaction products than the original components. In persistently wet conditions, sulphates will cause the concrete to expand and then to soften and disintegrate if their concentration is high.

### *Soft water leaching and efflorescence*

Soluble salts in the cement, such as sodium, calcium, potassium, magnesium and lime compounds, may be carried to the surface and crystallise as white deposits, called efflorescence. With evaporation, the salts accumulate at the surface.

The degree and rate of attack is dependent on the composition and permeability of the concrete, the presence of water (in areas where the concrete remains wet for long periods, it is more vulnerable to efflorescence), and the amount and solubility of the salts and lime compounds. Lime compounds, which are present in fresh cement and lime concrete, react with some components of the cement paste. Soft water that percolates through fine cracks or porous areas of concrete will dissolve minute quantities of lime out of the cement matrix. This leaching by soft water through the structure is characterised by powdery efflorescence, deposits of calcite, or growths of stalactites at the water exit points.

While not particularly damaging in itself, efflorescence indicates other potential problems such as water entry, which will corrode reinforcement and eventually result in loss of strength. Sustained leaching can leave the aggregate supported by only a weak silica skeleton and, if severe, can cause the cement matrix to disintegrate progressively inward from the surface. It may also cause crack openings to widen, resulting in a general loss of strength. Where leaching has been underway for some time, particles of aggregate can be seen in the runoff deposit.

## 4.3.4 Fire

Concrete has good fire-resisting properties and its thermal insulating properties are such that the effects of high temperature are absorbed rapidly within the thickness of concrete. Consequently, damage is usually confined to the zone close to the external surface of the structural element.

When exposed to high temperatures, concrete undergoes chemical changes that affect its strength and thermal properties. The heat of a fire evaporates moisture from the pores of the concrete.

Concrete undergoes distinct colour changes as its temperature passes through several bands (Table 1). Following a fire, the external surface of concrete may be discoloured and blackened, possibly suggesting total disaster. Concrete spalling is a common and frequent result that occurs more prominently at corners of column and beam sections, where high temperatures have been experienced on two sides.

TABLE 1. COLOUR OF CONCRETE UNDER TEMPERATURES OF 0–1000°C.

| COLOUR | TEMPERATURE RANGE (°C) |
|---|---|
| Normal | 0–300 |
| Pink | 300–600 |
| Whitish-grey | 600–900 |
| Buff | 900–1000 |

Reinforcing steel similarly experiences a loss in strength as a result of high temperature. In practice, the steel is protected by the concrete cover, and the temperature at the face of the reinforcing bar may be significantly less than at the face of the concrete member. However, exposed reinforcing transmits heat rapidly, which can dramatically increase the extent of fire damage.

The assessment of fire damage and its effects on the building structure require an appraisal, including a detailed visual inspection, extensive concrete testing and perhaps structural analysis of effective members. A history of fire damage can readily be assessed by the presence of spalled and/or pink-coloured concrete indicating likely fire damage.

# 5. Types of defects and deterioration in historic concrete

Concrete deterioration processes can be extremely complex and their identification prior to repair is not always easy. The most common defects and forms of deterioration in concrete are:

- Cracking
- Spalling and delamination
- Corrosion of reinforcing
- Disintegration
- Abrasion
- Staining
- Efflorescence and *crypto-florescence*
- Etching

## 5.1 CRACKING

A large range of types of cracks can be found in historic concrete structures, and there are a variety of possible reasons for their occurrence. In this section, an attempt is made to identify some of the most common types and to give an indication of possible underlying causes, to assist in the process of analysis and repair. The consequences of cracks depend on their type, their position, the type of structure and the aggressiveness of the environment. The presence of cracks exacerbates and initiates other problems, such as spalling, steel corrosion, and the ingress of aggressive substances from the environment.

Cracking occurs as a result of either changes in the volume of the concrete or loads that exceed the concrete's strength because of its tensile weakness.

The pattern and positioning of the cracking can assist in identifying its cause. Cracks can occur both in fresh plastic concrete during setting and in hardened concrete.

### 5.1.1 Plastic concrete

Cracking in fresh concrete results from plastic shrinkage and plastic settlement.

#### *Plastic shrinkage cracks*

Plastic shrinkage cracks usually occur in flat surfaces such as slabs. They typically taper very steeply, are random or parallel, and do not extend to the edge of the slab. They are often described as hairline cracks.

#### *Plastic settlement cracks*

Plastic settlement most often occurs in structural elements such as beams, columns and walls. Resultant cracks (Fig. 16) are caused by restraint during the consolidation of fresh concrete and by subsequent settlement; for example, they may occur where reinforcing steel or formwork causes obstruction during settlement, or where large changes in depth of section occur. These cracks, although wide at the surface, are often not deep.

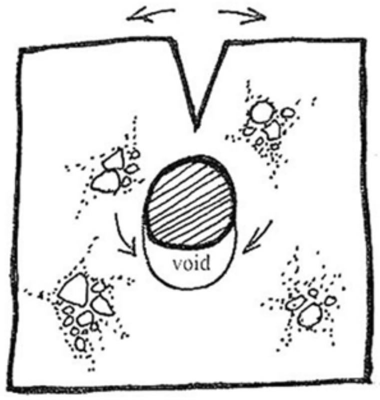



Figure 16. Typical settlement crack.

### 5.1.2 Hardened concrete

#### *Crazing and map cracking*

Crazing is a term used to describe extremely fine cracks that usually occur in a random pattern on the surface. They are most readily visible when they retain water just after the surface has dried. These cracks are very fine and not deep, as they penetrate only the surface. They are caused by differential thermal movement, differential moisture movement, carbonation, or alkali-silica reaction. Crazing is not a serious form of deterioration on its own and can be self-healing. However, the cracks do provide openings through which moisture and other aggressive agents can enter the concrete. Freeze-thaw cycles can then cause serious damage to the surface.

Map cracking is a more serious form of crazing. Map cracks are deeper and wider and less likely to be self-healing. They can be serious in aggressive or exposed environments because they allow water to penetrate more deeply into the concrete. As with crazing, map cracks are usually caused by differential movement between concrete near the surface and the mass, by the effects of freeze-thaw cycles, by internal chemical reactions, or by volume change of the material below the surface. In locations such as retaining walls, the cracks are sometimes marked by salt deposits. This indicates the leaching of soluble salts from ground water or of lime from the cement matrix.

### *Long and short edge cracks*

Edge cracks are commonly found running parallel to a joint or an edge of a surface. Edge cracking occurs because of the vulnerability of edges and corners to wetting and drying, and is usually exacerbated by freeze-thaw cycles. Cracks running along the edges usually precede spalling and disintegration at the edge or joint. Short edge cracks are less regularly patterned than long edge cracks, but are found in the same locations and are caused by the same process.

### *Parallel cracks*

Parallel cracking indicates the corrosion of reinforcement, with the cracks following the lines of the reinforcing. Rust stains commonly appear on the surface around the crack. These cracks allow moisture to penetrate the concrete, increasing the rate of corrosion of the reinforcing; the cracks then open further as the expansive forces of corrosion increase. The deterioration is progressive and the concrete surface will eventually spall along the crack, exposing the steel to further corrosion (Fig. 17).

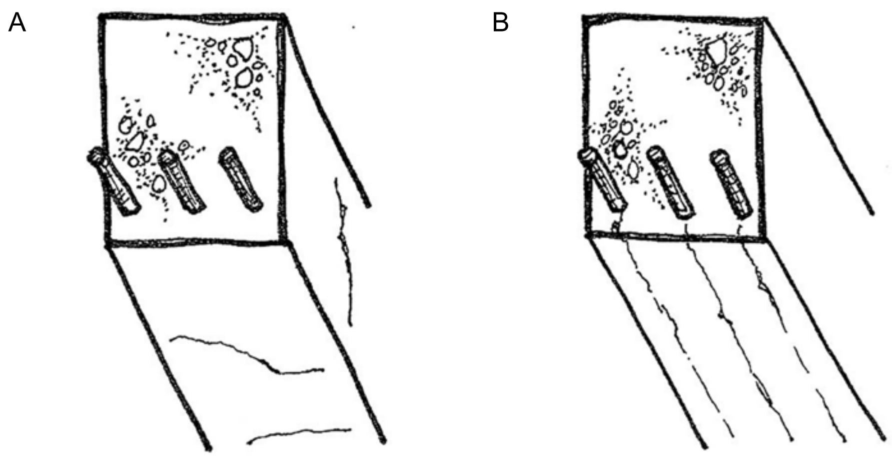



Figure 17. Cracks that run across reinforcing (A) are less likely to lead to corrosion than parallel-running cracks (B).

### *Long cracks*

Long isolated cracks that seem to be unrelated to any of the above problems can sometimes be found in concrete structures. These could be caused by initial drying shrinkage. Alternatively, if these are active, they may be due to insufficient allowance in the design of the structure for expansion and contraction due to changes in moisture and temperature. These usually run across slabs or surfaces that have no construction or expansion joints. They also occur at openings or changes of section where the concrete is restrained. To determine whether they are active, crack widths need to be measured at regular intervals over a period of time. This can be conveniently done with a small portable 'loop' viewer or monocular microscope.

### *Structural cracking*

Structural cracking is unlike shrinkage or temperature cracking and is caused by forces on the structure. Checking the location and direction of an imposed load should help to diagnose these cracks. They will generally be found in areas where tensile or shear stress in the concrete can be expected. The main danger from structural cracks is the possibility of structural failure, but such cracks will also allow and hasten deterioration due to moisture, corrosion and aggressive agents from the environment.

### *Stress cracking*

Stress cracking is often found at construction joints or cold joints that occur between pours of concrete. These joints represent planes of weakness in the concrete, so that when stress is applied to the concrete it is more vulnerable to cracking at these sites. Stress in the concrete can be caused by differential expansion and contraction of the adjacent pours. This can be exacerbated by inconsistent batching of the concrete, which can result in concrete of differing thermal and moisture movement between pours.

## 5.2 SPALLING AND DELAMINATION

Spalling is an unsightly process that results in concrete breaking away from the surface as a result of internal expansive forces (Fig. 18). Spalling often develops from cracks but can also be found where there is disintegration caused by freeze-thaw cycles. Once the spalled surface of the concrete is removed, there is usually no other evidence of deterioration and the underlying concrete is sound.

The most significant cause of spalling in historic structures is the internal pressure exerted by rusting metal reinforcement or fittings in the concrete, and the cause is usually obvious. Unreinforced structures can also experience spalling as the result of freeze-thaw cycles and this can be exacerbated by carbonation (see section 4.3.2). Freeze-thaw cycles will occur when freezing temperatures occur and moisture can penetrate the surface of the concrete (as occurs in porous concrete, cracked or crazed areas, where wood is left in the concrete, or at cold joint interfaces).

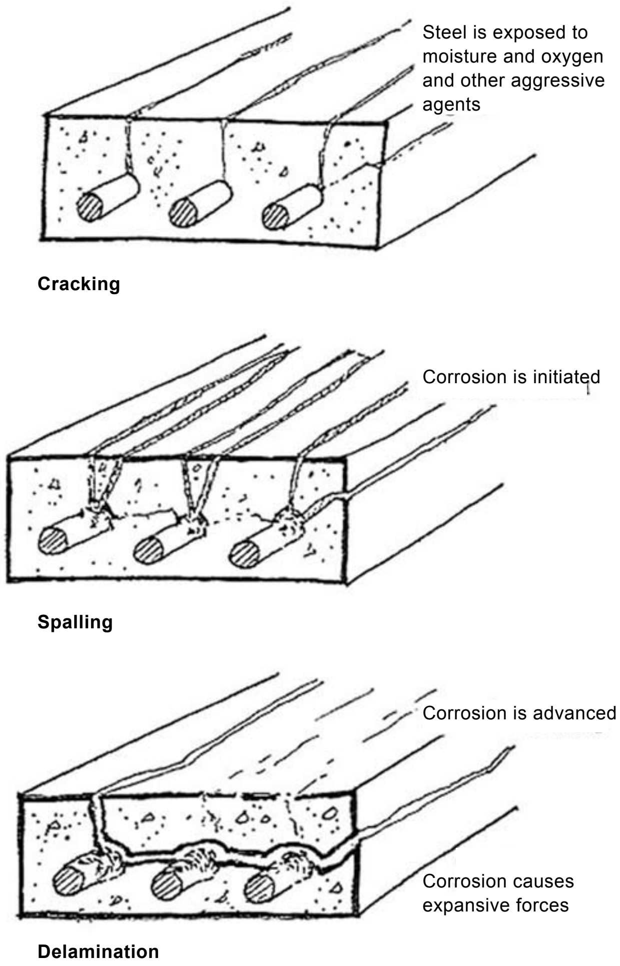



Figure 18. Progression from cracking to spalling to delamination in corroding reinforced concrete.

Spalling is a serious defect as it inevitably worsens, often rapidly. Concern about structural safety may arise due to substantial losses of concrete from the structure, and related corrosion and weakening of the reinforcing.

## 5.3 CORROSION OF REINFORCING

Corrosion of reinforcing is one of the most common defects in concrete. It can cause a significant loss of strength in the structure. Corrosion occurs when the reinforcing iron or steel is exposed to water and oxygen or to other more aggressive elements. It occurs in low-quality, permeable concrete that has inadequate coverage of its reinforcing. It is aggravated by an aggressive environment, chlorides, carbonation and acid attack.

The product of corrosion—rust—can have more than three times the volume of the original steel, resulting in expansive forces in the concrete. These both cause and exacerbate cracking, and later spalling and delamination.

## 5.4 DISINTEGRATION

Disintegrating concrete is loose and soft, and has little or no strength, depending on the severity. Disintegration occurs as a result of attack by chemicals such as sulphates, crypto-florescence (see section 5.7), or freeze-thaw cycles. If the concrete is cracked and porous, and has defects resulting from poor workmanship or materials, it will be more vulnerable to aggressive conditions. Marine structures at tidal level are particularly vulnerable to wetting and drying cycles, and their disintegration is compounded by abrasion from the movement of sea water. Under these conditions, usually only the strongest and most dense concrete can survive. Wetting and drying disintegration progresses from the outside-in, while sulphate and crypto-florescence often occur from the inside-out. Disintegrated concrete is not a superficial problem; thus, wholesale removal and replacement of concrete is often required.

## 5.5 ABRASION

Abrasion is an external condition only, which is caused by movement of an object or medium across the surface of the concrete, e.g. constant exposure to sea action. The effects of abrasion reflect the direction of the movement. Often the cement and aggregate are uniformly abraded, but the aggregate is more likely to be exposed as the cement base wears away. Depending on the severity, abrasion can cause substantial loss of material, which in turn can affect the structural stability of the member. Loss of surface material can make the structure more vulnerable to weathering and will reduce the cover to reinforcing.

## 5.6 STAINING

Stains are generally not harmful to a structure but can detract from its aesthetic value. Graffiti and stains from iron and steel rust, copper, bronze, petroleum oils, bitumen, paint, atmospheric dirt, and plants and micro-organisms will often be found on historic concrete. Stain removal often requires specialist expertise. Concrete, especially historic concrete, is a porous material and tends to soak stains into its surface. Some stains can be particularly stubborn as they react chemically with the concrete, in which case the only way to remove them may be to disguise them or make them less visible (see section 7.1.6).

## 5.7 EFFLORESCENCE AND CRYPTO-FLORESCENCE

Efflorescence is caused by soluble salts moving to the surface of the concrete and crystallising there (see section 4.3.3). Where efflorescence occurs, it can generally be seen as whitish crystalline deposits on concrete that is drying out after a long wet period.

Crypto-florescence occurs where salts crystallise beneath the surface and cause blistering of the surface. It is potentially more harmful than efflorescence and, if severe and sustained by the constant presence of moisture, can cause crumbling and disintegration of the concrete as the salts expand (see section 4.3.3).

## 5.8 ETCHING

Etching can result in only slight roughening of the surface or can be deep, as in a gouged-out channel. It is caused by the runoff of acidic water (especially in industrial areas), which reacts with the alkali cement. Thus, the surface damage to the concrete is often in a pattern that indicates the path of water runoff. It can also result from carelessness, e.g. by workers tipping sugary dregs from teacups onto the concrete surface. Etching may leave the aggregate protruding beyond the surface, giving it a rough texture—cement paste is abraded more readily than aggregates. Some forms of plant growth, particularly lichens, also cause etching (see section 4.3.3).

# 6. Investigation and evaluation of historic concrete

Regardless of the condition of a historic structure and the causes of its deterioration, the success of any concrete repair project will be determined by the quality of investigation, supplemented by testing and analysis. The investigation and evaluation of a historic concrete structure should preferably be undertaken by researchers, engineers or architects who are experienced in both concrete and conservation, and should cover:

- Research and document review
- Field survey, including site record, photographs and freehand drawings
- Testing
- Measured drawings
- Risk analysis
- Analysis and report

Once this has been arranged, the most appropriate conservation strategies can be determined based on a sound and thorough understanding of the structure. These areas are outlined in more detail below, and a case study is provided in Appendix 1.

## 6.1 RESEARCH AND DOCUMENT REVIEW

Original documents and information relating to the structure may or may not exist. If they do, these can be an invaluable aid in conservation. Every attempt should be made to find such documentation or records as they may provide information on:

- The intended composition of the concrete mix
- Finishes to concrete in the form of asphalt roofing or plaster renderings
- The type and location of reinforcing bars
- Original details that may have been lost or damaged
- Sources of raw materials
- Special foundation conditions
- Mixing and placement methods
- The proportions of the original concrete mix
- Records of later alterations, additions or repairs

Such documentation is commonly kept in archives by city councils and government departments (or the National Archives). Architectural and engineering firms generally preserve old drawings, and heritage bodies such as the New Zealand Historic Places Trust and local historical societies may already have information on file. Local libraries will have local history files with information and photographs.

### 6.1.1 Original documentation and records

Original documentation and records can be found in the form of original architects' or engineers' drawings and specifications, standard government department specifications, site records, and progress reports. Other sources may include company records, such as receipt or cheque books, order forms and day books.

### 6.1.2 Later documentation of repairs, alteration and additions to the structure

Later documentation may exist that shows changes, previous repairs, alterations or additions that took place over the lifetime of the structure. Again, these will be in the form of architects' and engineers' drawings and specifications, government department specifications, site records, progress reports, or valuation records.

### 6.1.3 Documentation on similar structures

Another possible source of information may be documents for buildings of the same type, construction or age. These could give an indication of the materials, design details and building construction methods likely to have been used. Contemporary or earlier text books may also explain practices and theories of the day that influenced the original builders in their choice of materials and work practices.

### 6.1.4 Local history

Knowledge of local history and local sources of materials can also be of assistance in determining the likely composition of concrete mix and for identifying causes of deterioration. It may be helpful to locate and interview people who were familiar with the site of the structure at an earlier time.

### 6.1.5 Old photographs

Old photographs are invaluable for establishing the historic appearance of an old structure and, where they have been taken over a period of years, may help to determine the rate of deterioration. They may also contain clues to environmental conditions associated with the site that may have had an effect on the durability or performance of the concrete structure. Such photographs can be especially useful in conjunction with on-site inspection of the concrete.

### 6.1.6 News reports

Newspapers often reported on new structures at the time of construction and later on alterations, repairs or additions. Building, construction, engineering and architectural journals may contain detailed information on the structure and proposed materials or methods of construction.

### 6.1.7 Conservation plans

In New Zealand, it is common for conservation plans to be prepared for historic structures. Where one already exists, it should include reference to all the above information and should include a condition survey conducted at the time it was prepared. A copy may be kept by the New Zealand Historic Places Trust, local historical society, heritage consultant, the owner or the local council.

## 6.2 FIELD SURVEY

In a field survey, characteristics of the structure and site are recorded in the following ways:

- Site record and condition assessment
- Photographs
- Freehand drawings

***Site record and condition assessment***

A thorough visual examination of the structure and its context should be undertaken. A record should be made of:

- The site and its conditions, including nearby structures or services, drains, pipes, ditches, the fall of the ground, retaining walls, the type of soil, boundary walls or fences. (Depending on the economy, scale of the project and size of the structure, this may be in the form of a full site survey carried out with surveying equipment, or a few simple level checks and site notes.)
- The structure and its materials and finishes, including what can be determined about the type of foundations, floor slabs, walls, roofing materials, window and door openings, detailing, and services such as electrical or water reticulation.
- The condition of the structure generally.
- The type, extent and position of any visible deterioration, with detailed notes on the apparent cause and the reasons for failure.

Section 4 outlines the forms of deterioration likely to be found in historic concrete structures, and may assist with the last point above. Things to look out for are cracks (of a range of types), spalling, delamination, disintegration, abrasion, stains, efflorescence, etching, damp and rusting steel. Although certain categories of defects, such as cracks, spalls and rust stain marks, can be visually obvious, other symptoms of deterioration, such as dampness, discoloration or honeycombing, may not be so readily detectable. Thus, experience with concrete structures will be necessary for some effects to be accurately identified. This fact alone strongly supports the need for specialists to supervise or conduct such inspections.

The site record should be cross-referenced to freehand drawings and photographs, to accurately record the location of information gathered and the position and extent of any deterioration. The results of the visual inspection will also be used to determine locations for sampling and testing.

### 6.2.1 Photographs

The structure should be photographed to record its current condition. Photographs should document the structure both generally and in detail, and should record evidence of deterioration. There should therefore be photographs of:

- The structure in its context
- Related site features that may have an impact on the structure
- Foundations and retaining wall details where these can be seen
- Each elevation
- Details, materials and finishes, including those of materials other than concrete that are part of the structure
- Interior views of all internal spaces and relevant details
- Photographs of the structure from above (where possible) and roofing details
- All visible deterioration in the structure

When photographing, the usual care should be taken to ensure that the correct exposure and lighting is used. It can be difficult to record surface texture, cracks, etc. if the light is from the wrong direction. It may be necessary to take photographs at different times of the day and in both sunny and overcast conditions. It may help to have the sun behind the photographer, to use photographic flash for detail shots, or to compensate for back light by over-exposing the shot somewhat.

### 6.2.2 Freehand drawings

The structure should be measured and freehand drawings made as part of the field survey. These should be dimensioned (using running dimensions and a few overall dimensions) and should include:

- A site plan, noting detail of the surrounding site, vegetation, orientation and any items that may affect the structure
- A plan, or plans if there is more than one level
- Elevations from all sides
- Retaining walls or information on foundations that can be ascertained
- A roof plan if applicable
- Any other relevant details

Notes from the site record should be cross-referenced to these freehand drawings. The freehand drawings may be used to produce more formal measured drawings; it may be necessary to return to the site for this purpose if the initial record is not sufficient or accurate.

## 6.3 TESTING

There is a large variation in the cost, reliability and type of information provided by the different methods of testing available. The extent of testing will depend on the nature of the project, the allocation of funding and the feasibility. This section aims to give those managing the structure a general knowledge of the testing methods that are available to assist in the analysis and evaluation of repairs that may be required.

A range of on-site, non-destructive tests can be undertaken. Laboratory testing can also be used to supplement the field condition survey and on-site testing as necessary. Laboratory testing will require samples to be taken on site. These can be in the form of lump, sawn or core samples. However, core samples may be difficult to obtain on remote sites, as a power source and water are necessary for the use of a *core drill*. It may also be inappropriate and disfiguring to take such samples from a historic structure; thus, discretion and judgement are required. The number and position of samples taken should be designed to give as accurate an assessment of the structure as possible, taking into account that the concrete may not be uniform.

A well-equipped concrete laboratory can analyse the samples for strength, unit weight, alkalinity, carbonation, porosity, alkali-aggregate reaction, presence of chlorides and past composition. Such tests can determine approximate mix proportions and cement content. Thus, laboratory testing can aid the formulation of a compatible design mix for repair materials to historic concrete.

### 6.3.1 Measurement of crack movement

The known history of a structure may be sufficient to determine whether there is continuing crack movement. However, where this is not obvious, there are several ways, of varied sophistication, by which movement can be determined (Fig. 19), including:

- Placing tape across the crack: the tape will wrinkle when the crack closes and tear when it opens
- Placing concrete nails on either side of the crack as measurement reference points (although inserting these may also cause damage)
- Fixing a thin piece of glass across the crack: the glass will crack open when the crack widens and splinter when it closes
- Setting up a scratch gauge, using some clear acrylic sheeting and a sharp object
- Using a specially designed proprietary measuring gauge to establish the exact amount of movement
- Using a strain gauge to measure the stress carried at a point of a structural member or across a fracture

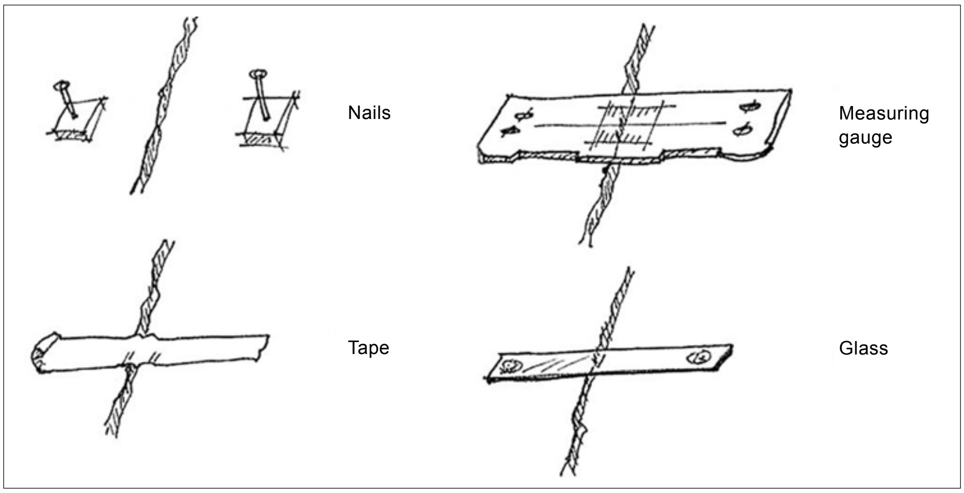



Figure 19. Measuring movement in concrete (after BRANZ 1998).

### 6.3.2 Corrosion in reinforced concrete

Testing for the likelihood, extent and rate of corrosion of reinforcement can be carried out in a number of ways.

#### *Concrete resistivity*

Resistivity measures the ease with which an electrical charge is transported in concrete, indicating the capacity of the concrete to either promote or retard corrosion. If the resistivity is high, the corrosion current will be small and corrosion will be unlikely. Resistivity relates to the type of concrete cover and does not measure environmental influences such as carbonation, chlorides, or temperature and humidity. The technique enables rapid scanning of the concrete using contact probes and requires specialist expertise.

#### *Half cell potential mapping*

Potential mapping provides information on the likelihood and extent of corrosion, but not on the rate of corrosion. The technique uses a half cell reference electrode connected via a voltmeter to the steel reinforcement, which becomes the other half cell. It therefore requires access to the reinforcing bars. The circuit is completed with a sponge saturated in water. The technique requires specialist expertise.

#### *Polarisation resistance*

Polarisation resistance measures the rate of corrosion. This can be a very useful measure when combined with chemical analysis of carbonation extent and chloride levels. This technique requires specialist expertise.

### 6.3.3 Chemical analysis

Laboratory tests on samples can ascertain the:

- Cement and aggregate content (calcareous and siliceous)
- Original water content
- Binder type, i.e. Portland or blended cements
- Presence of alkalis
- Chloride content
- Sulphate content
- Depth of carbonation

A number of ready-to-use chemical test kits are commercially available, but these require some experience for good interpretation. Chemical analysis can give an indication of possible and potential problem sources. A relatively simple test to measure the depth of carbonation on a fresh concrete sample uses a phenolphthalein solution, which changes colour at $pH > 9.5$; a bright pink result indicates that carbonation has not occurred in those areas.

### 6.3.4 Petrographic testing

Petrographic testing can be done on samples removed from the structure *in situ*. These tests provide information about the mineralogy and microstructure of the concrete, and are distinct from the chemical tests. They can provide information on air content, proportions of aggregate, cement and air voids, concrete homogeneity, and crack location. They should be undertaken by an experienced petrographer.

### 6.3.5 Reinforcing

A number of techniques can be used to measure the position, size and depth of the reinforcing, all of which require sophisticated equipment.

#### *Cover meter*

This is a battery-powered instrument that measures the size of the reinforcement, and its direction and depth below the surface. In areas of congested reinforcement, these may be difficult to read and unreliable. A range of cover meters that vary in sophistication are on the market.

#### *Gamma radiography*

A gamma radiograph can be used to estimate the location, condition and size of reinforcing bars, as well as voids and density of the concrete. This equipment is expensive and its use has to be tightly controlled due to radiation hazards. Experienced technical expertise is required.

### 6.3.6 Strength and quality

#### *Tapping*

Tapping is a very simple and useful way of detecting potential spalls or delamination of concrete. Voids can be readily detected by 'sounding' with a small metal hammer or even a pocket knife.

### *Rebound hammer*

A rebound hammer has a spring-loaded hardened plunger that strikes the surface of the concrete at a predetermined velocity: the harder the concrete, the greater the rebound. A measure of the rebound can be compared to empirical values, which can then be used to interpret the probable strength of the concrete. It is especially useful to determine the differences in concrete within the same structure.

### *Soniscope*

A soniscope measures the ultrasonic pulse velocity (UPV) of the concrete. This technique measures the travel time of an ultrasonic pulse through concrete to establish its compressive strength and degree of uniformity and quality. This determines the effect of freeze-thaw action and detects cracks. It requires a high level of expertise.

### *Radar detection*

Radar detection is similar to gamma radiography but less frequently used, despite being simpler. It can assess concrete defects and thickness.

### 6.3.7 Water permeability

Areas of walls may be tested by spraying water at the walls from the outside and then inspecting the interior to determine which areas are allowing moisture to penetrate to the building interior. If leaks are not readily apparent, sophisticated equipment is available to measure the water permeability of concrete walls. Such testing requires technical expertise.

## 6.4 MEASURED DRAWINGS

The records made on site, together with photographs and freehand drawings, can be used to produce accurate measured drawings of the structure. The measured drawings should document the structure as it stands at the present time. The date should be prominently noted on the drawings and they should be titled ‘measured drawing’. They should include:

- A site plan and key site features (recommended scale 1:100, but this will depend on structure and site). Depending on the project, this could be a full survey or a simple plan showing the orientation of the structure.
- Retaining walls and visible foundations (recommended scale 1:50).
- Plans of all levels (recommended scale 1:50).
- Elevations of each side (recommended scale 1:50).
- A roof plan (recommended scale 1:50).
- Relevant details (scales of 1:20, 1:10, 1:5).

On measured drawings, it is good practice to show only what is accurately known and not information that is surmised. If information is uncertain, this fact should be noted on the drawings. The structure is drawn as it exists at the time of drawing. For example, if there were walls that have been removed and their position is clear, these can be shown in dotted lines, with a note made of their removal and the date if this is known. Any alterations or additions are drawn as they stand and their date is noted if known. The drawings should be accurately to scale and the scale noted, in which case it is not necessary to dimension them.

## 6.5 ANALYSIS AND REPORT

Preparing a report is the final step in the process of evaluating the structure. The information gathered through the research and document review, field survey and documentation, testing, and measured drawings should be assembled to assist in the analysis of the structure. Since experience with concrete structures is necessary for sound analysis, specialists should supervise or conduct the analysis. The report should contain an overall description and assessment of the structure, including its general condition and any fabric that has been displaced, removed or added. The analysis and report will focus particularly on deterioration, as well as recommended actions to remedy identified faults, and should include:

- The type and position of deterioration, based on the investigation, the visual inspection, and the results of on-site and laboratory tests.
- The reason for the deterioration and the apparent cause of failure where this has occurred.
- The degree of deterioration—an assessment of the depth and extent needs to be made based on visual inspection, and on-site and laboratory tests. The condition of the concrete in high-stress areas and the condition (or existence) of reinforcing steel should also be assessed.
- Identification of risks to the structure and to the public.
- Cost-benefit analysis of alternative repair strategies.
- Recommended maintenance procedures following repair.

The report should summarise the condition of the concrete under the following broad headings:

### *Causes of deterioration*

Section 4 outlines possible causes for deterioration in historic concrete. These can be summarised as follows:

- Materials used in the original work
- Building practices and workmanship
- Effects of moisture, chemical agents, temperature and design

Together with an assessment of the local conditions, these will assist in identifying the causes of deterioration.

### *Rate of deterioration and aggressiveness of the environment*

The visual inspection, test results and local conditions can be compared with previous documentation to contribute to an assessment of the likely rate of future deterioration.

### *Possible consequences of continuing deterioration*

Section 5 outlines the consequences of different types of deterioration. Together with analysis of the degree and rate of deterioration, identification of the type of deterioration can assist in determining the possible consequences of continuing deterioration. For example, minor spalling may result in more serious delamination later, or an old structural crack may have settled and be no longer active but may be allowing water to penetrate the structure. Some of this information may be best presented in a table. Finally, the report should include the analysis, measured drawings, photographs and an appendix containing copies of existing documentation.

A cost-benefit analysis will also assist in determining a prudent course of action, and will provide a comparative basis for assessing alternative methods of repair to arrive at an optimum solution.

# 7. Repairs to defective and deteriorating concrete

It is essential that the cause of visually defective concrete be diagnosed and the necessity for intervention be carefully established before repairs are undertaken. The importance of a diagnostic investigation cannot be over-emphasised. The nature of deterioration in concrete that has remained essentially sound and cohesive for many decades before requiring repair is quite different from that of new concrete requiring repair after a very short period in service.

The primary focus should initially be to identify and eliminate underlying and aggravating causes of deterioration wherever this is possible. For example, circumstantial problems due to such things as drainage and damp, tree root systems, plant growth, excessive loading, and other aggressive agents should be resolved where possible.

This should be followed by formulation of a repair strategy for retention, protection and maintenance of the structure based on the principle of minimum intervention in keeping with good conservation practice. The repair should arrest deterioration, ensure structural integrity that is compatible with the intended use of the structure, and should not detract from the intrinsic character and historic value of the structure.

Assessment of concrete repair requires an understanding of available techniques, and it will generally be essential to obtain professional appraisal of a structure by a qualified engineer with experience in the repair of historic structures. The range of available repair methods includes:

- Traditional repair
- Re-alkalisation
- Desalination
- Cathodic protection
- Corrosion inhibitors
- Incipient anode effect

## 7.1 REPAIR OF CHARACTERISTIC DEFECTS

### 7.1.1 Cracking

Before cracks are repaired, it is essential to determine whether they are active or dormant, and whether corrosion of reinforcing has been initiated. These factors will all influence the type of repair required. Repair that is undertaken as soon as possible after the onset of cracks will be easier and will prevent much more serious and expensive problems later. If corrosion of reinforcing steel has been initiated, it is important that this is repaired first, as otherwise the continuing corrosion process will cause failure of the repair. Narrow *dormant cracks* and those that cross the reinforcing are less likely to hasten corrosion than wider cracks, *active cracks* or cracks that run parallel to the reinforcing. Dormant cracks generally present lesser problems than active cracks, as deterioration from them is slower. Active cracks are more likely to be larger and filled with water and debris, which can restrict movement and may lead to further cracking.

Dormant cracks can be self-healing and may not need repair if small. If they do need repair, they can be filled with a rigid filler that is compatible with the base concrete. Active cracks should not be treated with rigid fillers, as the ongoing movement will either cause failure of the repair or transfer the stress and introduce cracking elsewhere. Instead, to be successful, repair must either remove the cause of movement (following which a rigid filler can be used), or allow for continuing movement through the use of a flexible sealant.

There are many techniques for crack repair, including specialist injection techniques, crack filling, elastic joining, and the use of load-bearing connections. It is important that the correct technique is used, and it is recommended that careful analysis of the cracking and of the structure as a whole be undertaken by experienced consultants. Some guidelines for crack repairs are set out below.

#### *Dormant or stable cracks*

Hairline cracks that are dormant need not be repaired—as a rough guide, this includes cracks that are no greater than 0.3 mm wide (BRANZ 1998).

If the crack is stable and clean, and no corrosion is present, it can be simply grouted with a material that is compatible with the base concrete, such as modern epoxy grouts.

If the crack is stable but weathered and filled with debris such as moss, the adjacent concrete should be cut away square so that there is no feathering around the edges, cleaned thoroughly, filled with a material that is compatible with the base concrete, and properly cured.

### *Active cracks*

If the crack is active, the movement in the structure must be analysed and taken into account when designing an appropriate repair method. If the movement is not likely to be eliminated, the crack must be filled with a sealant that will remain flexible and water-resistant (Figs 20 & 21).

If corrosion of the reinforcement has started, it must be treated before crack repairs are done.

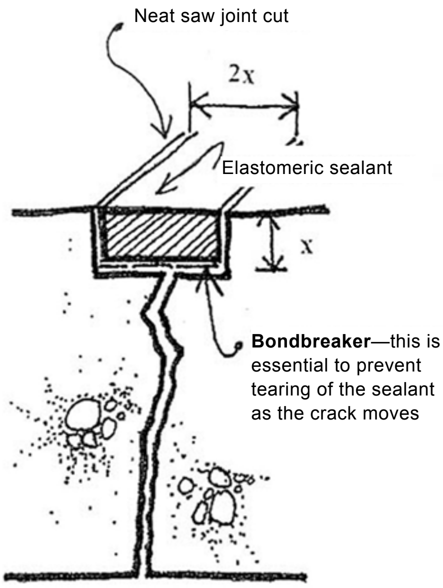



Figure 20. Repair of an active crack.

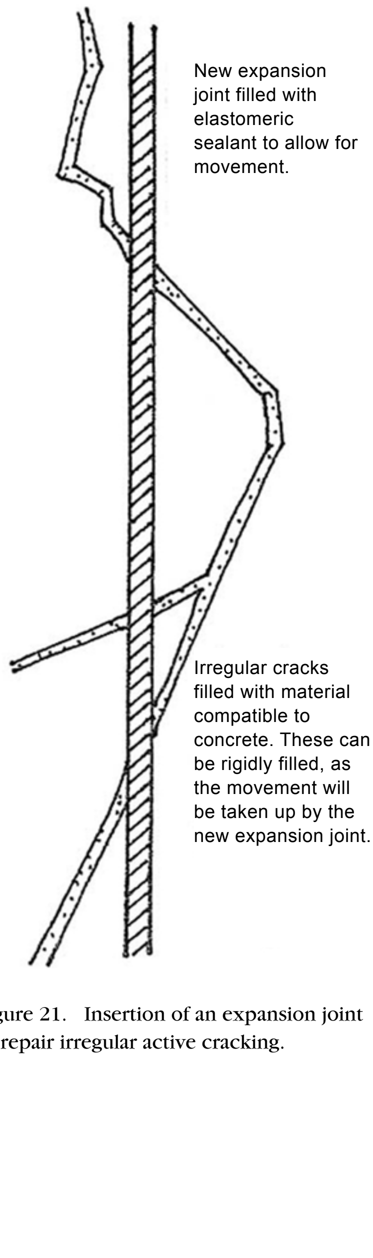



Figure 21. Insertion of an expansion joint to repair irregular active cracking.

### 7.1.2 Spalling

Spalling is repaired by cutting all loose and deteriorated concrete back to sound concrete and far enough back behind the reinforcing to allow corrosion to be removed from the iron or steel. Before replacing the lost concrete, corrosion must be neutralised and, if necessary, additional steel reinforcing placed (see section 7.1.3). If spalling is extensive, a structural engineer must assess the structure for stability and determine whether any additional support is necessary before, during and after repair of the structure.

### 7.1.3 Corrosion of reinforcing

Once deteriorated concrete has been removed, the reinforcing must be thoroughly cleaned and sections replaced where necessary. The steel can be sealed with protective coatings to prevent further deterioration. Where it is not possible to achieve a sufficient degree of cleanliness of the steel and where aggressive environments continue to be a threat, it may be appropriate to consider electrochemical procedures to protect the steel from corrosion.

The strength of the structure should be assessed by a structural engineer, who will determine whether the reinforcing needs to be replaced or supplemented. In some cases, it may be concluded that reinforcing is, in fact, not necessary in a given location (early reinforced structures may have reinforcing in inappropriate places, or the structure may no longer be required to carry the original design loads), in which case the bars can be treated and left, or simply removed.

Where it is not possible to achieve a sufficient concrete cover over the reinforcing, it may be necessary to use materials that have better corrosion resistance than steel, e.g. stainless steel or, more recently, glass or carbon fibre. Any of these options will involve additional expense in the short term but will probably be the most cost-effective in the long term.

### 7.1.4 Disintegration

Disintegrating concrete must be cut out and removed down to sound concrete. Careful analysis of the reason for disintegration is necessary, and the cause should be isolated and either removed, physically altered or minimised. Disintegration may be due to soft water leaching, sulphate attack, crypto-florescence, acid attack or freeze-thaw cycles, and may be exacerbated by carbonation in the presence of high carbon dioxide levels (see section 4.3). The cause must, therefore, be recognised and the solution designed accordingly.

Where removal of the cause is not practicable, it may be necessary to rebuild sections of the concrete with a material that is more resistant to the aggressive environment or to apply protective surface coatings. Careful design and expertise is required for this process so that new sections are compatible with original material. Drastic solutions need to take account of heritage values and good conservation practice, and should seek to minimise the loss of those values.

### 7.1.5 Abrasion

Natural weathering is sometimes regarded as part of the character of a historic structure. In some cases, however, the loss of surface material leads to exposure of aggregate over time, resulting in deterioration of the concrete, in which case it may be necessary to take protective measures.

Where possible, the source of abrasion should be removed. Often this is not possible, however. For example, it would not be possible in sea or tidal areas, where the continuous action of water may cause extreme abrasion. In this case, it may be necessary to treat the concrete with high-impact epoxy impregnation or to coat the structure with abrasion-resistant polyurethane. It is now accepted that only really high-quality concrete—preferably precast in factory-controlled conditions—can withstand the abrasive forces of sea movement and associated chlorides.

Where disintegration has occurred, careful design and expertise is required in repair to ensure that new materials are compatible with the original and do not introduce new factors that may cause older sections to deteriorate even faster.

### 7.1.6 Stains

In some instances, the natural consequences of ageing of historic concrete may be considered part of its heritage character. Stains may, however, be unsightly and may be associated with more serious problems. Identifying the cause of the stain is, therefore, the first and most critical step in the process of repair. If removal is determined to be necessary, the sooner a stain is removed the better.

Most stains can be removed, but this will require specialist knowledge, as different techniques work in different situations, and the process of removal can be extremely damaging to the base material. There is an extensive literature on the subject, which focuses on the chemistry of both the substrate and the staining agent to identify the most appropriate method of treatment.

As a general principle, it is desirable to start with the mildest method of cleaning before resorting to stronger methods. A test should first be carried out on a small, inconspicuous section to determine the effectiveness of the method and to check for side-effects. Methods of removal include:

- Hand scrubbing with water (the mildest).
- Mechanical methods, such as brushing, scouring, water blasting or blasting with nutshells, steam cleaning or flame cleaning (these can be useful but may roughen the surface to an unacceptable degree).
- Removal with chemicals (can be effective but requires specialist knowledge, as damage to the concrete can readily occur). For example, white aluminium stains on concrete can be cleaned with a weak solution of 1 part hydrochloric acid to 15 parts water, gradually increasing in strength as necessary; the concrete must be thoroughly rinsed with clean water afterwards.
- Dissolving with a carefully designed *poultice* (a smooth paste that is applied over the stain). The liquid in the poultice migrates into the concrete,

dissolves the stain material and then migrates back to the poultice. The active agent finally evaporates and leaves the staining material in the poultice. Repeated applications are usually needed.

- Decolorising so that they are less visible. This is usually done by wiping the surface with a suitable chemical—again, specialist knowledge of the type of stain and the active agent is needed.

### 7.1.7 Efflorescence

Recurring efflorescence can be minimised through preventive measures. However, it may take months—and sometimes years—for active efflorescence to cease. Efflorescence flourishes in the presence of moisture; therefore, it will only cease with the removal of the source of moisture. Moisture may have come from the concrete itself, but in older concretes it is more likely to be from exposure to rain or from water leaching through the ground into the concrete. It is therefore desirable to keep the concrete dry and to drain leaching ground water away from the structure, especially if the water is chemically soft. Sources of sulphate contamination should be removed from contaminated ground water.

It is unwise to seal concrete afflicted with efflorescence, as this prevents evaporation, trapping the salt crystals within the material. This may cause internal deterioration, crumbling and disintegration, which are characteristic of crypto-florescence.

Depending on its severity, surface efflorescence can be dry brushed from the surface, scrubbed off with water or hosed with water under high pressure. Dilute solutions of acids are effective in removing stubborn efflorescence, but care needs to be taken, as all acids can etch and may damage the concrete and adjacent materials. Typical acidic washes for the removal of efflorescence include:

- 1 part hydrochloric acid to 9–19 parts water
- 1 part phosphoric acid to 9 parts water
- 1 part phosphoric acid to 1 part acetic acid to 19 parts water

The concrete surface should be thoroughly hosed and saturated with water before and after treatment. Any use of acid must be undertaken with great caution, as there is a high risk of some acid remaining in the pores of the concrete, causing etching.

### 7.1.8 Crypto-florescence

Crypto-florescence is caused by the same mechanism as efflorescence but occurs below the surface, resulting in blistering of the surface and disintegration. Where it is not severe, the root causes and effects should be treated as for efflorescence. However, if crypto-florescence is advanced and disintegration of the concrete has occurred, it will have to be cut back to sound concrete and replaced with a *compatible material* (see also section 7.1.4). The application of protective coatings—particularly silicones—to the surface may aggravate crypto-florescence where it occurs.

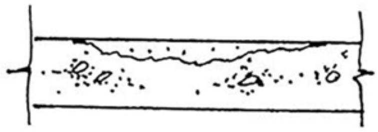
### 7.1.9 Etching

Where etching of the surface has occurred, it will be necessary to identify the source of acidic attack, e.g. acid rainwater run-off. When this source has been dealt with, the surface of the concrete should be thoroughly cleaned and, if the etching is severe, the affected area may need to be cut back and replaced with compatible concrete, ensuring good matching and bonding of the new material to the old.

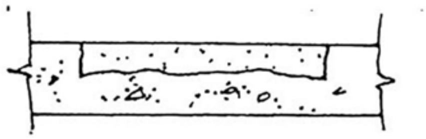
## 7.2 PREPARATION FOR REPAIRS

### 7.2.1 Concrete removal

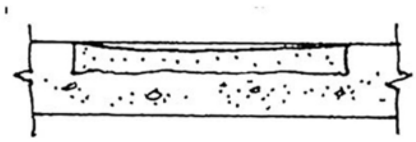
When removing the concrete, it is essential to ensure structural stability; therefore, it may be necessary to provide temporary support to the structure. When determining the amount of concrete to be removed, areas of loose and deteriorated concrete as well as areas affected by corrosion must be defined. The method of removal will depend on feasibility, safety and economy. The depth of removal will depend on the severity of deterioration. Where reinforcement corrosion has occurred, the concrete should be removed to 20 mm behind the affected reinforcing bars so that these can be treated. Concrete should be removed by saw cutting or other methods that do not result in cuts with *feathered edges* (Fig. 22).



**Incorrectly installed patch**—patches with feathered edges will soon break down.



**Correctly installed patch**—the chipped out area should be at least 25 mm deep with the edges perpendicular.



**Result of incorrect finishing of patch**—if the patch is struck off to the level of the concrete, the patch will sag in the centre.

**Correct method of finishing**—the strike off board is held slightly above the level of the concrete. A thorough curing process should follow to prevent shrinkage cracking.

Figure 22. Patching concrete (after Fulton & Crawford 1966).

### 7.2.2 Surface preparation of concrete

Following concrete removal, the exposed surface should be sound, crack-free, and free of loose concrete. It should be clean of dust and any contamination such as grease or oil. Surfaces that have been treated with curing membranes or silicones must be removed, as these will retard the adhesion and curing of patch material. Surface preparation is extremely important for the success of the repair.

### 7.2.3 Preparation of reinforcing iron and steel

Corroded steel should be cleaned back to clean metal. The original reinforcing should be retained wherever possible. Removal of the rust can be done with wire brushing, chiselling, water jetting or sand blasting. Corrosion of reinforcing leads to reduction in the effective cross-sectional area and strength of the steel, and the repair may need to compensate for this loss through the introduction of supplementary reinforcing.

In highly corrosive environments, protective coatings such as epoxy or zinc coatings can be applied immediately after cleaning has been completed to prevent rust formation before the application of repair mortar. The use of such coatings on exposed reinforcement is no longer considered essential and is generally only applied to bars exposed to highly corrosive environments, to prevent rust formation before the application of repair mortar.

## 7.3 MATERIALS

### 7.3.1 Choice of materials

The best repair material is concrete that has properties matching as closely as possible those of the concrete being repaired. Modern repair mortars, while being roughly twice as strong as old concrete, have similar elastic stiffness and so do not result in problems of compatibility. The material should bond well with the substrate and should result in minimum aesthetic change to the surface. It should also be dimensionally compatible with the original and should have the same behaviour under thermal and loading conditions. Repair materials should also be compatible with the environment.

The repair material should be no stronger than the base material, as this can cause damage to the original concrete. In particular, repairs incorporating modern Portland cement should be carefully designed to match the lower strength of an older material.

Cementitious materials are usually the most suitable for repairs, but there are a range of useful products that can supplement these depending on the situation. The advantage of cement-based materials is that they can be carefully proportioned to obtain properties and strength matching the base concrete. The disadvantages are that they may have poor adherence and may suffer shrinkage. This can be partially overcome by ensuring low water:cement ratios, and good workmanship, placing and curing. Admixtures can be used to minimise shrinkage, but must be used with care to avoid excessive air-entrainment.

For both cementitious and epoxy repairs, bonding agents can be used to improve bonding to the substrate. Caution should be taken with these bond coats, however, as they may impede natural moisture movement in the concrete and, in some cases, lower the pH of the concrete, increasing the vulnerability of the reinforcing to corrosion. Contact between steel and a repair material can be improved with a cement slurry coating or a zinc epoxy bond primer.

Every repair is unique and has unique conditions. For example, it may be necessary to obtain rapid strength gain under restricted work conditions, or to achieve additional chemical or abrasion resistance. This may not be possible simply by matching the base concrete with a cementitious repair material alone. There are many concrete repair products commercially available, including polymer-modified cement concretes, polymer impregnation techniques, protective coatings, *elastomeric sealants*, epoxy resins, admixtures and bonding agents. It is important that these are carefully evaluated for appropriateness before use. The manufacturer's full literature and field-test data should be requested or examined before making a final selection, and that specialist knowledge should be employed wherever possible.

### 7.3.2 Hydraulic lime concrete

Hydraulic lime is difficult to obtain today. Although small quantities are produced in Europe, most lime produced in New Zealand is non-hydraulic or not sufficiently hydraulic for the production of lime concrete. However, natural hydraulic lime can be imitated in two ways—by the addition of pozzolanic material to *non-hydraulic lime*, or by the careful proportioning of white or general purpose cement with non-hydraulic lime.

Natural pozzolans are available in the form of volcanic ash or can be produced from crushed burnt clay products, such as bricks and tiles. Artificial pozzolans are manufactured as high-temperature insulation (HTI) powder and pulverised fly ash (PFA). HTI powder is a finely ground, fired, china clay, which is white in colour and can be useful for the conservation of lime concrete. PFA is obtained from coal-burning fire stations and, when added to lime, makes an effective grout for filling fissures in lime concrete; however, its dark colour can be a problem and it is important to ensure that the ash is not contaminated with sulphate.

### 7.3.3 Portland cements and general purpose cement

Early Portland cement tended to produce concretes that were weaker than modern general purpose cement concrete. However, the fact that modern repair mortars may be twice as strong as old concretes does not create problems of compatibility, as the two materials have similar plastic stiffness. The dispersal of stress between old material and new repair will depend on a number of factors, including the relative shrinkage of the new material and support given to the components of the structure during repair.

It may be desirable to match the new repair to the old in appearance, to achieve some aesthetic continuity. The use of white Portland cement and well-chosen aggregates will assist in colour matching.

### 7.3.4 Polymer-modified concrete

Polymer-modified concrete is produced using cement that has been gauged with acrylic polymer or styrene butadiene latex to improve bond, reduce shrinkage and permeability, and make the mixture more plastic. Care needs to be taken, as excessive amounts of air can be entrained in these mixes and there is also a risk that the pH of the concrete may be lowered through their use.

Admixtures or air-entrainers, expanders, retarders, accelerators and water reducers can play an important role in conservation repairs. In some cases, they will improve the quality of the repair medium, alter its physical characteristics, reduce shrinkage and increase frost resistance. Admixtures should enhance good workmanship; they are not a substitute for it. They are obtainable as pre-mixes and with bonding agents. In all cases, their suitability for the specific application should be carefully checked.

### 7.3.5 Bonding agents

Where bonding is difficult, a number of proprietary bonding agents are available for use. Caution should be used with these, as polyvinyl acetate (PVA) bonding agents can lower the pH of the concrete. Some are unsuitable in damp situations, while others form moisture barriers that can restrict the moisture flow within the material.

### 7.3.6 Aggregates

Aggregates are used in the normal manner for new work. Careful selection and *grading* of aggregate will help achieve a satisfactory texture and colour match with existing material. Since it may not always be possible to identify the aggregate used in the original concrete or the source of it may no longer be accessible, a knowledge of alternative sources will be an asset.

### 7.3.7 Metals

Metals are used for reinforcement repairs and the keying-in of patches. Conventional mild steel reinforcement is used for tensile stressing and reinforcing large areas of recasting. Non-ferrous metals are used for stitches and armatures or where minimal concrete cover is unavoidable. The principal metals used are copper, phosphor-bronze, stainless steel and mild steel.

### 7.3.8 Epoxy and zinc coatings for steel

Epoxy and epoxy with zinc are the most commonly used protective coatings for steel. In addition, good concrete cover will help to prevent corrosion of the reinforcing steel.

### 7.3.9 Polymer concrete and epoxy resin

Polymer concrete is typically 100% solid epoxy resin and aggregate. It is suitable only for dormant cracks, and can be used where a high chemical resistance or rapid curing is required, or where conventional curing cannot be carried out. Treatment with epoxy resin requires specialised skill.

### 7.3.10 Polymer impregnation

Highly permeable low-grade concrete can be upgraded *in situ* by impregnation with an epoxy polymer. Strengths of up to four times the original concrete can be achieved. Treatment requires specialised skill.

### 7.3.11 Elastomeric and flexible sealants

Cracks that have occurred where insufficient design provision has been made for thermal or moisture movement will continue to be active. As a general principle, these should be repaired with flexible sealants, but where some structural load needs to be carried or transferred through the affected section, modern epoxy adhesives are capable of providing a sufficiently strong bond. Where some resilience is desirable to accommodate movement, this can be allowed for in the design of the adhesive. However, elastomeric or flexible sealants alone will not restore structural strength.

There is a wide range of flexible sealants available, including acrylic, polyurethane, polysulphide and silicone-based products. Choosing the correct sealant for the task at hand is important. Some are vulnerable to UV damage, discoloration, softening or hardening with exposure to weathering. Others are aggressively adhesive to delicate surfaces, such as some older concretes.

The correct design of repairs with elastomeric or flexible sealants is critical. It is important that a 'bond breaker' is used (Fig. 20). It is also necessary for the structure as a whole to be evaluated, so that the design of new expansion joints with flexible sealants can be considered to prevent further problems.

### 7.3.12 Protective coatings and moisture barrier systems

Following repair, protective coatings and moisture barrier systems may be applied in some circumstances to provide additional protection to the structure. These form films over the surface of the concrete, which act as barriers to chlorides, carbon dioxide and other aggressive agents. However, if moisture is trapped in the concrete, this can cause problems that completely negate the repairs undertaken. Therefore, although a coating must resist the ingress of water, it must also allow moisture to escape in the form of vapour. For this reason, epoxy resins are generally not appropriate for this purpose, as they are completely impermeable and do not 'breathe'.

There are now many products promoted as anti-carbonation coatings to limit the ingress of carbon dioxide while still allowing the passage of water vapour. There is, however, some debate over the real effectiveness of such coatings.

Acrylics and some other coatings allow outward diffusion of water vapour. The effectiveness of coatings should be checked before use. Good workmanship and good coverage are essential for achieving their full performance potential.

### 7.3.13 Specialist injection techniques

High- and low-pressure injection systems using specialised equipment can be used instead of grouting and trowelling for crack repairs. Materials for this include both rigid and flexible materials, such as cement-based systems, epoxy resins, polyurethane resins and foams, and acrylic gels.

## 7.4 TREATMENT OF REINFORCING IRON AND STEEL

The main cause of reinforcement corrosion is low cover to the reinforcement and, to a lesser extent, poor quality concrete. Corrosion due to the presence of chlorides, whether added as calcium chloride or absorbed, is less common than that caused by insufficient cover, but when it does occur its effects may be wide-ranging. Where there is insufficient cover of concrete over the reinforcing steel, carbonation-induced corrosion of reinforcement may result, either in conjunction with or independently of chloride-induced corrosion.

Where it is not practical to achieve a sufficient degree of cleanliness of the steel, several different electrochemical processes can be considered for the protection of steel reinforcing. All of these are still gaining acceptance and require special expertise. These techniques are less destructive and mean that less extensive cleaning of reinforcing is necessary. Such systems have to be carefully designed, however, because they can cause softening or damage to the concrete. Some of the available methods are outlined below.

### 7.4.1 Cathodic protection

For many years, cathodic protection has been used successfully for reversing the process of corrosion on civil engineering structures. The technique is used primarily against chloride attack. It is based on the principle of reversing the flow of electrical currents that sustain the corrosion process. Corrosion involves a small electrical current flow at the anode on the reinforcement whilst the cathode is protected. With cathodic protection, a permanent external current source is connected to the reinforcing system via a conductive medium. This then reverses the current flow, so that the reinforcement becomes a cathode and so is protected.

There are two forms of cathodic protection:

- Sacrificial anode system: A conductive paint or a titanium mesh can be placed permanently on the face of the concrete. The reinforcement and sacrificial anodes are connected to a DC power supply that regulates the current flow. The sacrificial anode corrodes and is replaced at the end of its design life (5–10 years for conductive paint and 25+ years for titanium mesh).
- Impressed Current Cathodic Protection (ICCP): Cathodic protection can be applied if the metal to be protected is coupled to the negative pole of a direct current source, while the positive pole is coupled to an auxiliary anode. There is no need for the anode to be more active than the structure to be protected. This is a permanent feature and requires monitoring throughout the life of the system.

Both the sacrificial anode system and ICCP are usually built into a structure and are not easily fitted retrospectively.

### 7.4.2 Desalination (chloride extraction)

Desalination is appropriate for chloride-contaminated concrete. The natural alkalinity of concrete surrounding reinforcement may be reduced by the presence of chlorides and, in the presence of moisture, pitting corrosion of the reinforcement may occur.

Chloride extraction is carried out once. Excess chloride ions may be extracted from the concrete by this electrochemical process, during which the chlorides are repelled from the reinforcement towards an external anode. A titanium mesh anode is placed with calcium hydroxide (as a slurry) in a cassette shutter on the face of the concrete. A low-voltage DC current is passed through the concrete to achieve a pre-selected current density. When this is achieved, desalination is complete, although measurement of the chloride levels in the concrete should also be undertaken.

If there is a danger of further chloride ingress, the structure must be protected with a chloride-proof coating.

### 7.4.3 Re-alkalisation

Re-alkalisation is a very similar process to the chloride extraction technique, but is used in carbonated concrete to restore the pH to its usual high alkalinity. As described in section 4.3.2, the natural alkalinity of concrete surrounding reinforcement provides protection against corrosion, but carbonation may slowly migrate to the depth of reinforcement, reducing the alkalinity and, in the presence of moisture, causing corrosion. Historically, carbonated but non-visually-defective concrete may have been broken out; however, where the concrete is otherwise sound, re-alkalisation may be appropriate.

Sodium carbonate is placed as a slurry in a cassette shutter on the face of the concrete; this reacts with carbon dioxide and water to migrate through the concrete, attracting the alkalis to the concrete surrounding the reinforcement. The slurry is held in position for several days until the process is complete. The steel reinforcing becomes passivated, thus halting and preventing corrosion. This process is non-destructive and, as for chloride extraction and cathodic protection, cleaning of the reinforcement is not as extensive as would otherwise be necessary.

Where spalling due to chloride attack or carbonation is not advanced, these methods can be applied as a preventive treatment before the damage sets in. In addition to these methods, there are new alkaline impregnations that are designed to reduce corrosion. These are applied to the concrete as an overlay or spray, which migrates through the pore structure and forms a protective passive coating on the steel. These are still being developed and their long-term effects are not known.

### 7.4.4 Corrosion inhibitors

Corrosion inhibitors are currently attracting widespread interest as a means of concrete repair. Many materials suppliers actively promote the use of corrosion inhibitors within concrete repair systems. There are two types of corrosion inhibitors, which work in fundamentally different ways:

- Inhibitors applied as an admixture to fresh concrete, e.g. calcium nitrate. These inhibitors have been used for many years and are considered to be largely effective.
- Inhibitors applied externally to hardened concrete, either as vapour-phase inhibitors or as migrating inhibitors, which penetrate through the concrete cover to the depth of reinforcement. The use of these is relatively new, and their effectiveness is yet to be proven in the long term. Nevertheless, there may be certain situations where their use is beneficial.

# 8. Conservation strategies

This section discusses a range of appropriate conservation strategies for deteriorated or defective concrete structures. It is intended to guide administrators, engineers and architects in the protection and repair of historic concrete. It should also assist in the design, specification, execution and supervision of works required to physically conserve historic concrete.

The following strategies are guided by the ICOMOS New Zealand Charter for the Conservation of Places of Cultural Heritage Value (ICOMOS 1996).

## 8.1 CONSULTATION AND REVIEW

Once the analysis and report on the structure has been completed (section 6), a process of consultation and review should be undertaken by the consultants involved and the owners or managers of the structure. This will be done in conjunction with determining the conservation strategies for the structure and will be informed by the analysis. The investigation and analysis will have ensured that detailed and accurate information about the condition of the structure is available.

It is necessary to determine what is possible with the available resources, including:

- Economy and funding availability
- Use and possible adaptation of the structure to prolong its life
- Local availability of the techniques and materials that may be considered

To do this effectively, wide consultation is necessary not only with the owner or organisation responsible for the structure, but also with other heritage and statutory bodies, such as the New Zealand Historic Places Trust, the territorial authority and its heritage section, contractors, product and service providers, and bodies who may offer funding assistance and grants for conservation work. This will ensure that all parties have been consulted and the best possible options have been explored within the parameters and resources available. Ideally, the specialists and consultants involved in the analysis should continue their contribution by helping to determine conservation strategies together with the owner or those managing the structure.

## 8.2 CONSERVATION STRATEGIES

The criteria for what constitutes an acceptable repair for a historic structure will often differ from those for a modern structure. Appropriate strategies will be guided by sound structural practice, sound conservation principles and a thorough analysis of the existing structure (Fig. 23).

For conservation purposes, the first option to be considered is a policy of preservation and minimum intervention that ensures the best long-term survival of the structure whilst at the same time retaining its heritage attributes. The best way to achieve this is to find an appropriate balance between preservation of original material and the addition of necessary new material to ensure the continued safety of the structure. When deciding what action should be taken, there should, therefore, be consideration of the retention and protection of the existing fabric.

The next step is to consider whether recovery of parts of the structure is appropriate and what repairs should be undertaken, depending on resources available. In all instances, the aim should be to find the best possible way to do this without compromising the heritage value of the structure.

Finally, any work that is undertaken should be documented for future reference and for establishing an ongoing process of maintaining and monitoring the structure. Working through the following strategies during the process of consultation and review will help to determine what action will be the most appropriate in each case.

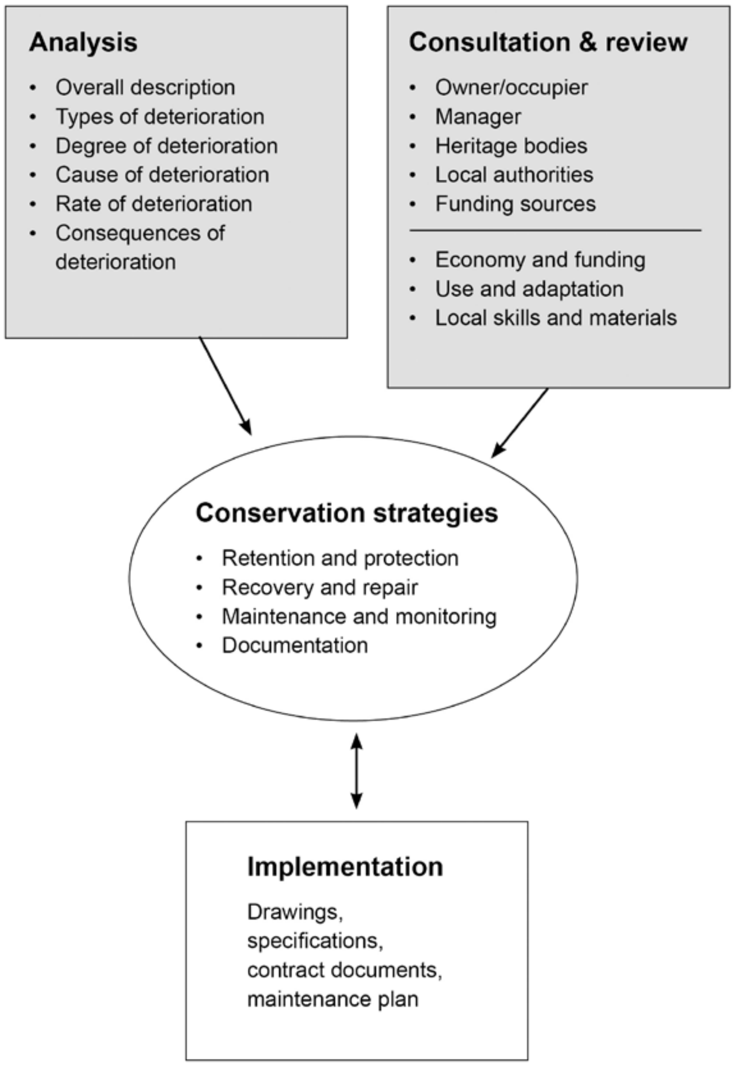



Figure 23. Determining conservation strategies for concrete buildings.

### 8.2.1 Strategy 1—Retention and protection

Any intervention should aim to retain cultural and historic significance of the structure through the necessary process of repair. For a historic building or structure, this may mean that what is new should be distinguishable from what is original. Stabilisation, risk mitigation, adaptation and interpretation may be involved in retention and protection of fabric.

#### *Stabilisation*

Where necessary, stabilisation of the structure is the first and most basic step to ensure its future survival. Preventing, arresting and slowing further decay can be achieved by removing the cause of deterioration, where possible, and by treating the existing fabric to slow or minimise further deterioration.

Sometimes a simple support can prevent further deterioration of a structure and ensure that it is safe. Such support should be reversible, so that a complete process of repair can be undertaken when and if this is possible or appropriate.

#### *Risk mitigation*

Any risks to the structure or that may be caused by the structure should be identified and appropriate steps taken to mitigate their effects. Damage to the structure could be from natural or other events, e.g. fire, graffiti, farm animals, over-use or plant invasion. Unsafe aspects of the structure could include loose material that could fall, and cavities or unprotected openings in which children or animals could be hurt. Each situation will require its own risk evaluation and action, e.g. fencing or covering the structure. Again, such measures should be reversible.

#### *Adaptation*

The likelihood of future protection of the structure can be greatly improved by ensuring that it fulfills a useful purpose. This can be social, cultural or economic. In some instances, adaptation of the structure may be necessary to achieve this. If additions are needed to adapt a structure, it should be clear what is new and what is original, while remaining sympathetic to the existing structure.

#### *Interpretation*

Interpretation of a place can increase public understanding and ensure that the structure is better protected. This can include brochures describing the structure and its background, signboards on the site, articles in local newspapers, or listings on historic site lists advertised by the New Zealand Historic Places Trust or the Department of Conservation.

### 8.2.2 Strategy 2—Recovery and repair

Where resources allow, recovery and repair of the structure is recommended to promote its long-term survival while maintaining its heritage value. Any intervention should aim to recover cultural and historic significance. Again, a policy of minimum intervention is recommended. In some instances, reconstruction of fabric may be appropriate. Several processes may be involved in restoring the structure to an earlier state, including removal of accretions, repair, reinstatement and reconstruction.

#### *Removal of accretions*

In some instances, structures may have had unsympathetic additions or fabric added that detract from the heritage value of the structure or may even be causing damage. Where possible, these should be removed and any affected fabric repaired or reinstated. Not all additions should, however, be regarded as accretions; if they add to the heritage value of the structure, they should be maintained. Where unsympathetic accretions are necessary and perform a useful function but detract from the heritage value, consideration should be given to their replacement with a more compatible solution.

#### *Repair*

It is not possible to draw up a simple table of materials and methods to cover all the situations that may be encountered during the repair of a concrete structure, and broad generalisations will propagate incorrect information. In every case, the selection of appropriate materials and methods should be with reference to the original materials used in the structure. Suitability for purpose must always be the aim.

In conservation, it is generally preferable to find materials that match the original in porosity, hardness and colour. The new material should be sacrificial to the original material rather than stronger than it, to avoid it causing further deterioration of the original material.

Techniques for repairing historic concrete structures have advanced greatly in recent years. Modern techniques can be based on the use of non-cementitious materials acting as *bonding mediums*, chemical binders, strengtheners, consolidants, and admixtures such as plasticisers. These materials primarily provide effective structural repair quickly; aesthetic considerations are secondary. Because such techniques are relatively new and have not been the subject of long-term experimentation and evaluation, common sense and compromise should be used when selecting a technique and deciding on the extent of work. Test all techniques and mixes before carrying out a repair.

Before selecting a repair method:

- Consider the performance required of the repair
- Bear in mind that repaired concrete may not be as sound as a monolithic mass of concrete

- Remember that in all repairs shrinkage must be minimised, compatible materials must be used and workmanship must be of the highest standard
- Consider a policy of non-intervention, monitoring, preventive maintenance and judicious neglect

***Reinstatement***

Items and fabric that have been displaced should be restored to their original position with the least additional material or intervention possible while still ensuring that the structure is sound and safe.

***Reconstruction***

Reconstruction could be considered to ensure functionality for the future survival of the structure or to promote understanding of its heritage and function. This should only be undertaken if enough documentary or physical evidence exists to inform reconstruction. As for repairs, reconstruction should be undertaken with original materials wherever possible.

### 8.2.3 Strategy 3—Maintenance and monitoring

It is unrealistic to assume that a repair project can solve all the problems of a historic concrete structure. It is recommended that a maintenance plan be drawn up that includes a 5-yearly inspection. This should include site visits, inspections, analysis, recommendations and preparation of maintenance schedules. Funding allocation for this process is necessary.

### 8.2.4 Strategy 4—Documentation

It is good conservation practice to document all work and procedures undertaken. This ensures that there is a record and history of any changes to the structure, so that information is available should further work be required in the future. This will also be useful to inform maintenance and monitoring of the structure. This can be done by way of photographs, drawings and specifications.

## 8.3 IMPLEMENTATION OF CONSERVATION STRATEGIES

Once the conservation strategies have been determined, they can be implemented. This will require the production of drawings, specifications and contract documents for the proposed work, preferably undertaken by those involved in the analysis and with technical and conservation expertise.

Work of this nature is often extremely difficult to estimate and price. Although the nature of the work may be known, a large part of the extent of work required will often have to be determined as the work progresses. One way of dealing with this problem is to use an agreed schedule of rates for specified operations with a chosen specialist contractor.

# 9. Field guidelines

The investigation and evaluation of a historic concrete structure should preferably be undertaken by researchers, engineers or architects who are experienced in both concrete and in conservation, as explained previously. It is recognised, however, that expert or experienced advice will not always be available to field staff. Therefore, the purpose of this section is to provide a basis for informed judgements to be made at the site by field staff.

Effective fieldwork will depend on:

- Sound preparation
- Careful observation
- Thorough recording
- Accurate analysis

## 9.1 PREPARATION

Before visiting a site, it is important to ensure that adequate and appropriate equipment is available for the field. It will also always be helpful to have located as much documentary evidence as possible and, in particular, to have consulted the historical record, to find out as much as possible about the site and the historic artefact itself. This may include a search of local and national archives, including those within DOC. The objective will be to find anything that helps to understand the object as it was built, including:

- Its purpose
- How it functioned
- Its construction
- The history of its use
- Changes made over time

This will provide clues that will help understand its present appearance and condition.

## 9.2 SITE OBSERVATION

Examination of the object and its site is a critical activity. It will be important to be able to distinguish the historic artefact from its present surroundings, and to differentiate significant material or components from material that is not relevant—it is always possible that other objects that were not part of the original have been dumped at the site. This is where the preliminary research will prove valuable.

Changes to the site may have concealed parts of the object, and changes to the object itself, including collapse or being covered over by later material, may confuse the visual analysis. An important principle, however, is to suspend judgement and note everything as if it is relevant, then determine later by analysis whether this is in fact the case.

## 9.3 RECORDING

Recording is a logical extension of site analysis, and is intended to ensure that all information established at the site is noted and stored in a systematic manner. This is important for later analysis away from the site, particularly if another person needs access to the same information. It also forms a crucial part of the case history of the artefact, and may provide a basis for comparisons to be made at a later date. The level of detail that will be appropriate will depend, to some extent, on the scale of the site, its various components and the extent to which these are dispersed over the site.

As described in section 6.2, the site record should note:

- The site and its conditions
- A description of the structure and its materials and finishes
- The condition of the structure generally
- The type, extent and position of any visible deterioration

Useful records combine graphic and textual material, and may also include sampling of materials.

Graphic records combine photography, plans and detail drawings. Plans and detail drawings should be carefully and neatly annotated to show where photos have been taken, and to record factual detail such as dimensions, as well as impressions of condition, colour and anything else that may be a characteristic of change over time. In all recording, begin with the general and contextual, and then move on to the detailed and specific. Bear in mind that most recording is likely to be undertaken on paper no larger than A4 size, hopefully on a clipboard (anything larger can be too difficult in adverse weather conditions). On every drawing sheet, note the following:

- Site name
- Location
- Date
- Name of the investigator/recorder
- Title of the drawing
- Page number

When drawing, use constant line size for general drawing, with heavier lines to show outlines or edges. Where parts of an object are clearly missing, use broken lines to indicate the missing material. Where components are overhead, use dotted lines, or for beams, etc., use centre-line notation of dashed/dotted line. The drawings should be dimensioned (using running dimensions and a few overall dimensions) and should include:

- **Location plan** This could be a photocopied road map or ordinance survey plan with the site marked and annotated with a GPS reference. Note access points or tracks, and other property interests.

- **Site plan** This should cover the whole site (or if the site is very large, the immediate locality of the artefact) to provide reference points to key landmarks or other distinguishing features (e.g. Fig. 24). Some objects may be difficult to locate visually because of overgrowth or decay, in which case reference points with dimensions from the object will be useful for others looking to locate the site. Note these dimensions, using triangulation wherever possible to get the best possible fix. Show the extent of the artefact in its immediate landscape and identify main physical features.

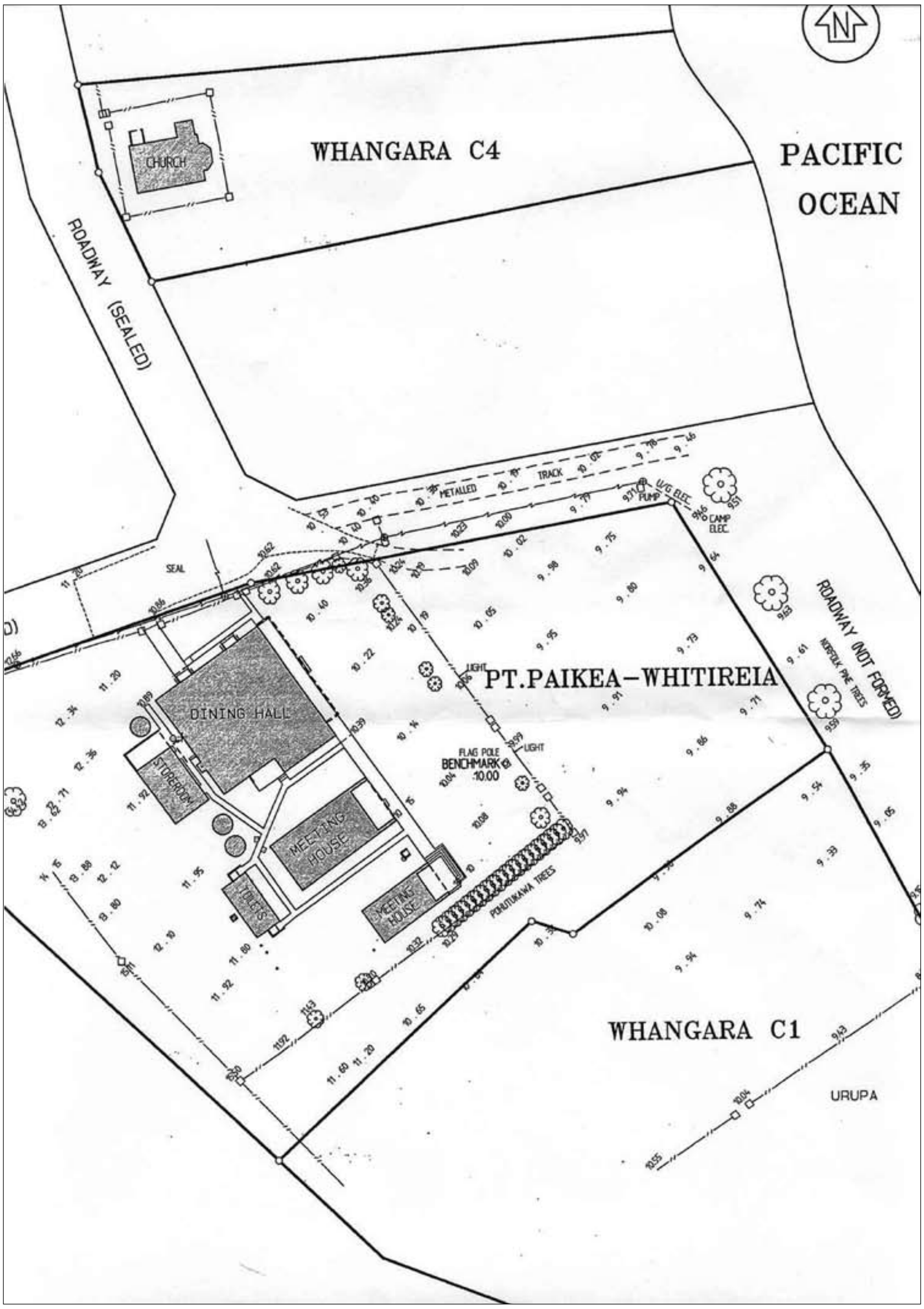



Figure 24. Surveyed site plan, showing key features, at Whangara Marae, near Gisborne (Grant & Cooke Ltd, Surveyors, Gisborne).

- **Detail plan** Draw the object again at a larger scale to provide plans at each level (including roof), showing key physical features in reasonable detail, with overall dimensions to show the relative position of the parts (e.g. Fig. 25). Use firm, clean lines to show main surface features, with thicker lines to show edges between main elements.
- **Elevations** Where possible, also sketch a view of the object from all sides, as close to the same scale as the plan. Similarly, note dimensions to show the relationship of the parts and heights above ground. It may be helpful to lightly shade some surfaces to show setback, or to use texture (such as dots) to indicate surface condition. Hatching (diagonal lines) is useful for indicating material covered over or missing.

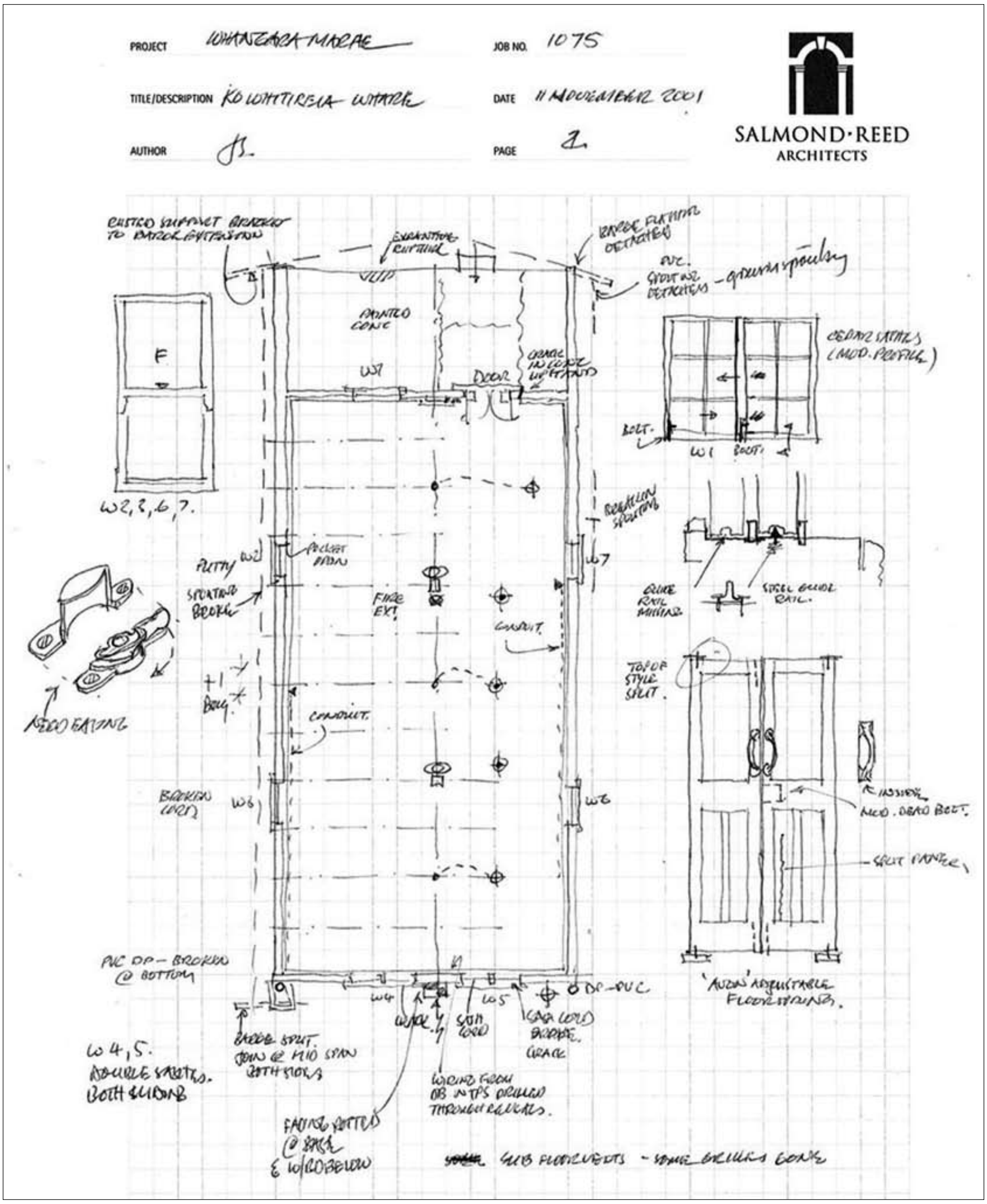



Figure 25. Site sketch plan for church at Whangara, near Gisborne, showing showing some construction details and recording the condition of various features.

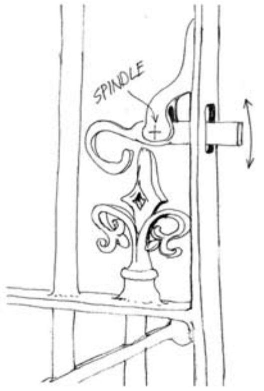



Figure 26. Sketch showing detail of door latch operation.

- **Details** It may be useful to make larger scale sketches of parts of the object to allow greater detail to be recorded, or to show how a particular component is made or may have functioned (e.g. Fig. 26).

Recording of the condition of the site and its artefacts may be adequately represented in notes on site drawings, together with photographs. However, it can be useful to also produce a table of items with observations noted, as ultimately the results of the inspection will need to be summarised in an accessible form for analysis, and tables provide a useful format for adding subsequent analysis and prescription for remedial works.

It may also be possible to take from the site samples of materials for analysis. This can be especially appropriate for materials such as concrete, since the precise nature of the concrete mix may require laboratory analysis to assist in determining a remedial process.

## 9.4 ANALYSIS

While some analysis will be possible at the site, a more considered conclusion may best be left until all evidence and information can be collated and compared. It is not always practicable to interpret archival material in the field, unless this has been thoroughly studied beforehand. On the other hand, copies of archival photographs may be enormously helpful for identifying otherwise formless items by their location on the site and relative to each other.

If possible, use the site drawings and measurements to produce accurate scale drawings of the site and the artefacts. These will be useful for analysis and will form a valuable record of the site at that point in time.

Post-site analysis allows considered examination of all the evidence from the site, from research, and also from analysis of samples that may have been taken at the site.

# 10. Acknowledgements

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# 13. Glossary of technical terms

**Active cracks** Cracks that open and close, usually due to changing environmental conditions.

**Bonding medium** Material used to bond fresh concrete to existing concrete.

**Carbonation** A slow chemical reaction between atmospheric carbon dioxide and cement paste. It results in a lowering of the pH of the concrete. It also hardens the concrete and reduces its permeability progressively inward, creating layers in the concrete that undergo differential movement. Carbonation is accompanied by some shrinkage.

**Cement** An adhesive composed of a *dry hydrate* made into a paste with water. It is most often associated with Portland cement (artificially manufactured cement).

**Cold joint** The point at which two adjacent pours of concrete meet. Because the first pour has already set and partially cured, the bond between the two surfaces is weaker than the rest of the concrete and can open under stress.

**Compatible materials** Materials that have similar characteristics of expansion and contraction under changing environmental conditions.

**Core drill** A tool used to remove a core sample of concrete on site. The sample may then be tested in a laboratory for strength, unit weight, approximate mix proportions and cement content.

**Crypto-florescence** Similar to efflorescence, but occurs below the concrete surface, causing blistering and disintegration.

**Curing** The maintenance of optimum moisture and temperature conditions to promote to the best advantage the hydration of the cement during the setting and hardening process. This can be achieved by adding moisture by sprinkling with water or covering with wet sand or hessian, or by preventing moisture loss using plastic sheeting or liquid membrane curing compounds.

**Dormant cracks** Cracks that no longer open or close.

**Dry hydrate** Dry powder. Can refer to either non-hydraulic lime, hydraulic lime or hydraulic cement.

**Drying shrinkage** Reduction in volume of the concrete when some of the water in excess of that required for hydration evaporates from the mass, causing shrinkage.

**Efflorescence** Formed from soluble salts such as magnesium, sodium and, to a lesser extent, calcium, potassium and lime compounds, which crystallise on the surface of the concrete in the form of a white powder.

**Elastomeric sealant** A sealing material that returns to its original shape when not under stress.

**Feathered edge** An edge to a cavity or crack that attains depth gradually and unevenly, as opposed to a steep, clean edge.

**Free water** All water contained by concrete, mortar or plaster in excess of that chemically held as water of crystallisation.

**Grading** The grading of aggregate refers to the quantities of particles of various sizes. Well graded aggregate has a continuous range of aggregate particle sizes.

**Hardening** The friable mass becomes progressively more tightly bonded together and less friable until it is firmly set.

**Honeycombing** Where a large part of the cement paste and fine aggregate was removed from the concrete during pouring, leaving voids of cement-coated large aggregate. It is usually caused by poor compaction or leaking formwork.

**Hydrated lime** Dry powdered lime, sometimes known as 'hydrate', 'dry hydrate' or 'bag lime'. Hydrated lime can be either hydraulic or non-hydraulic lime and is usually sold in paper sacks through builders' merchants.

**Hydration** A complex process that involves several simultaneous series of chemical reactions during which the main constituents of cement (the calcium silicates and aluminates) react with water to produce hydrates and numerous other compounds. The fact that the reaction products are insoluble gives concrete its characteristic durability in the presence of water.

**Hydraulic cement** See 'cement'.

**Hydraulic lime** Lime that sets and hardens under water because of the aluminium silicate or burnt clay content. Hydraulic limes can be separated into three loose categories: eminently hydraulic, moderately hydraulic and feebly hydraulic. (Cf. 'natural cement'.)

***In situ*** When used in the context of concrete structures, this means that the concrete was cast on site. Originally, this meant that the components of cement, fine aggregate, coarse aggregate and water were mixed on site as well. In recent times, however, concrete is often brought to the site pre-mixed and then cast on site.

**Lime putty** Putty-like substance that is created when an excess of water is used during the *slaking* process. Can be kept for long periods in an air-tight container.

**Mortar** A mix of fine sands, either *lime putty*, hydrated lime or Portland cement, and water. Used in the fabrication of brick or masonry work.

**Natural cement** The product of burning limestone, which, in its natural state, contains sufficient siliceous impurities (15%) to produce a lime with hydraulic properties. Natural cements set rapidly, even under water, but cannot be slaked in lump form. (Cf. 'hydraulic lime'.)

**Non-hydraulic lime** Slaked lime without any hydraulic properties. Can be known as pure lime. Non-hydraulic limes will not set under water. They take an initial weak set just by drying out and they only develop strength by the slow process of induration (the process of hardening) at the exposed surface.

**Portland cement** (Ordinary Portland cement—OPC.) The product of burning an artificially prepared and precisely controlled mixture of limestone and clay (silicates and aluminates) at approximately 1300°C. The resulting clinker is then finely ground to produce cement. Portland cement is now more usually known as 'general purpose' cement.

**Poultice** A mix of an inert fine powder with a solvent or solution for removing stains from concrete. These are blended into a smooth paste, which is then applied over the stain using a trowel or spatula. The solvent or solution permeates the concrete and dissolves the stain. It then gradually moves back into the poultice and evaporates, leaving some of the staining material in the poultice.

**Pozzolans** Materials containing silica, alumina and sometimes iron oxide. When combined with slaked hydrated lime, pozzolans add hydraulic properties to the lime. Natural pozzolans were found by the Romans near Mt Vesuvius in volcanic ashes from Pozzuoli, hence the name. Other natural pozzolans used in the past were terras or trass found in Germany on the banks of the upper Rhine, and volcanic ash (santourin) from Greece. Artificial pozzolans can be produced from crushed or burnt clay bricks and tiles, and (in more recent times) granulated blast furnace slag and pulverised fly ash.

**Quicklime** Calcium oxide—also known as 'lump lime' and 'unslaked lime'. Formed by heating raw limestone and other lime-rich materials in a kiln. This removes carbon dioxide from the stone leaving calcium oxide. Quicklime reacts with moisture to form calcium hydroxide; therefore, it must be handled with great care.

**Ramming** A historic method of consolidating concrete in the form, by pounding with a heavy wooden rammer until water began to appear at the surface.

**Reaction product** The compound resulting from a chemical reaction.

**Sand** A form of silica. May be classified according to its origin, e.g. pit sand, river sand and sea sand. Washed pit sand is preferred, as river sand has round, smooth grains that reduce adhesive value, and sea sand will be contaminated by salt, which will attract dampness and cause efflorescence in cured concrete.

**Segregation** Separation of the course aggregate from the cement, water and fine aggregate as a result of gravity or lateral movement of a wet mix or excess vibration.

**Setting** When a mixture of cement, aggregate and water loses its plasticity and becomes friable. It will not become plastic again upon mixing with water.

**Slaked lime** Quicklime that has been mixed with water to form calcium hydroxide. The reaction generates considerable heat and the product is highly corrosive.

**Slaking** The reaction that occurs when quicklime is mixed with water.

**Spalling** The loosening and subsequent loss of concrete from a structure due to expansive forces in the concrete. This usually occurs as a result of the expansive force of steel rusting: the rust from corrosion of steel has three or more times the volume of the original steel. A more serious form of spalling is delamination,which is when a whole layer of concrete comes loose from the structure.

**Vibrating** The current method of consolidating freshly poured concrete in the forms by immersing a vibrating head into the concrete.

**Water:cement ratio** The chief factor that controls strength for a given cement content. Water is needed to wet the surface of the aggregate and to hydrate the cement. All water additional to this is 'free water', which increases plasticity and workability, but reduces strength and durability.

**Workability** The ease with which good hydration of the cement takes place, and ease of placement in the forms and compaction of the concrete so that there are no voids.

# Appendix 1

## WATER TOWER, MOTUIHE ISLAND—CASE STUDY

### Introduction

The water tower on Motuihe Island, Hauraki Gulf, Auckland, was erected by the Navy in 1941 (Fig. A1.1). It was one of many structures built as part of rapid infrastructure development during WWII, and was erected to store sea water to be used for fire-fighting purposes. It comprised a round reinforced concrete tank supported on reinforced concrete posts with brick masonry infill panels. HMNZS Tamaki was a naval training base on the island and part of Auckland's WWII coastal defence complex.

Naval records from 1947 noted that the low-pressure water tower and the reticulation system for fire protection were built during the rush period of Tamaki's early development when it was considered to be a training establishment for the War period only, and that at this time it was already inadequate, as the site had now become a permanent training centre. Additional reservoirs were subsequently built to supplement the water supply for fire-fighting.

The first part of the process of investigation and conservation of the tower is outlined below. This serves to show a method for evaluating structures in the field. As outlined in section 6, investigation and evaluation cover:

- Research and document review
- Field survey, including site record, on-site testing, photographs and freehand drawings
- Measured drawings
- An analysis and report based on the above

In this instance, no testing was undertaken.

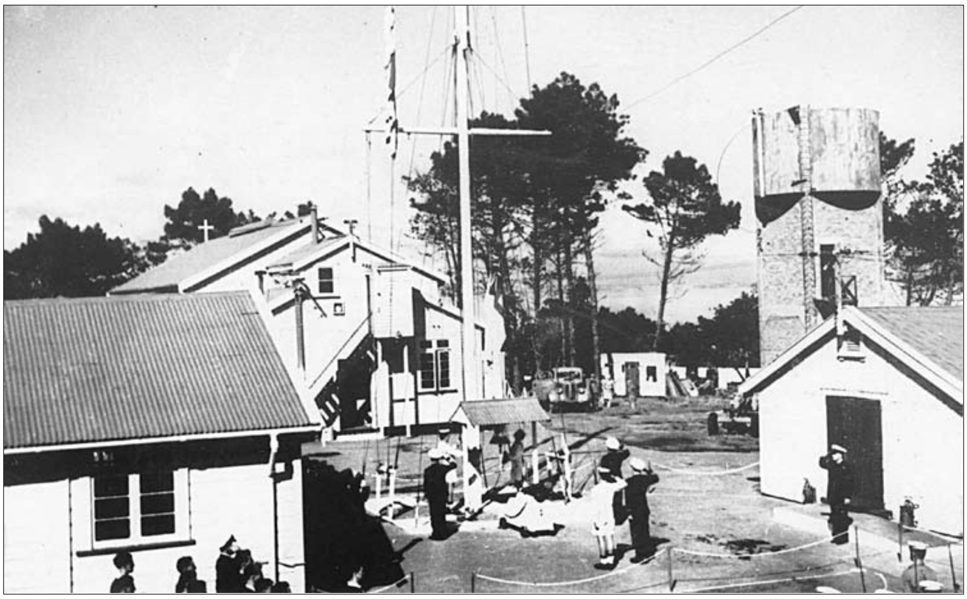


Figure A1.1. Water tower, Motuihe Island, near Auckland, c. 1950, showing structure with original doors, windows, and brickwork intact (held on file at Auckland Conservancy, DOC).

## Research and document review

Research at the National Archives into Public Works Department, Defence and Naval files indicated that the water tower was one of a number of structures built in 1941 for HMNZS Tamaki Naval Training Base. No original drawings or specifications were found for the structure.

There are extensive specifications for later concrete reservoirs built in the 1950s, which give details of not only materials and quantities, but also workmanship and curing of the concrete. It is not certain, however, that these specifications matched those for the water tower. As with many other defensive constructions of the time, the structure was built in a great hurry together with numerous other buildings on the site, and very little documentation survives.

## Local history and background

Records of the Tamaki site from 1948 noted that all construction materials had to be transported to the island. The concrete would have been based on ordinary Portland cement and well-graded, clean aggregate. It is possible that water for both the concrete mix and curing was contaminated with chloride. It is not known whether the construction was carried out by contractors or by defence force staff, and this may have affected the quality of workmanship—particularly the amount of concrete cover over reinforcing steel.

A number of old photographs and drawings have been located in National Archives, and copies of these are held by the Department of Conservation.

## Survey

### *Site conditions*

The water tank is situated on Motuihe Island in the Hauraki Gulf. The site is flat, in a high-wind area, and exposed to sea air and thus airborne chlorides. The site is remote and does not have general services such as an electricity supply. The water tank is the most prominent of the few surviving structures on the site. It is no longer used for water storage.

### *Structure*

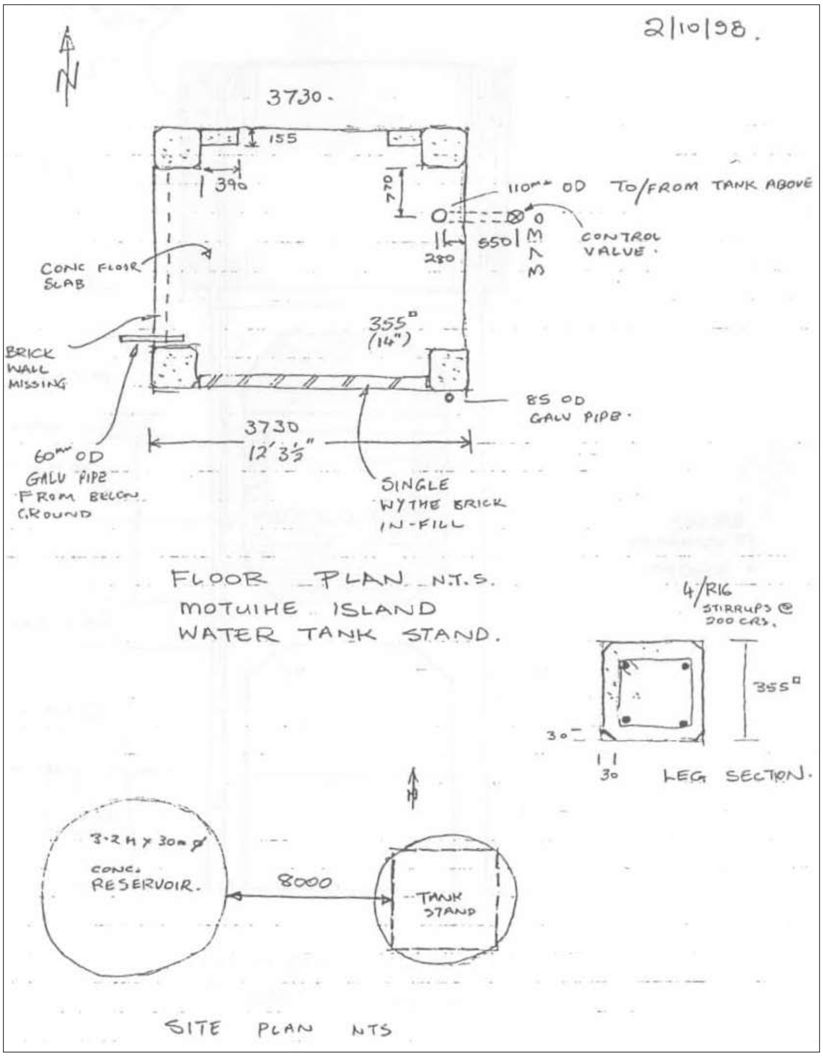
The structure has a reinforced concrete frame with brick infill panels (Fig. A1.2) supporting a circular, reinforced concrete water tank. Its overall height is 12.5 m and the tank is 5.2 m in diameter (Figs A1.3 & A1.4).

The structure is currently in poor condition, with deteriorating brick and concrete. The bricks of two of the brick infill panels have collapsed or have been removed, leaving some remaining brickwork unsupported. The site is generally untidy, with loose building rubble lying in and around the structure.

### *Visible defects and deterioration*

A range of distinct defects have been identified in both the concrete and the brick masonry. These are summarised below. A selection of photographs is included to explain the site context and to illustrate specific or characteristic defects.

Figure A1.2. Site plan and floor plan sketch of water tower, Motuihe Island, and surrounding buildings, late 1940s (held on file at Auckland Conservancy, DOC)..



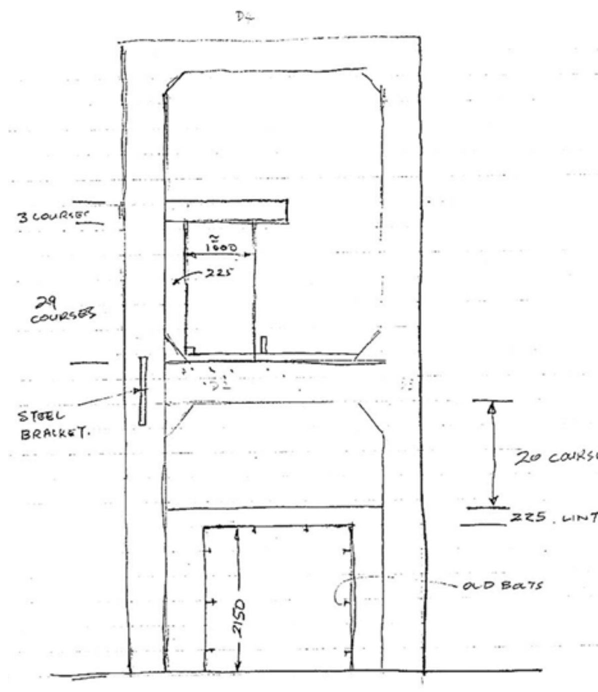




Figure A1.3. North elevation of water tank, Motuihe Island.

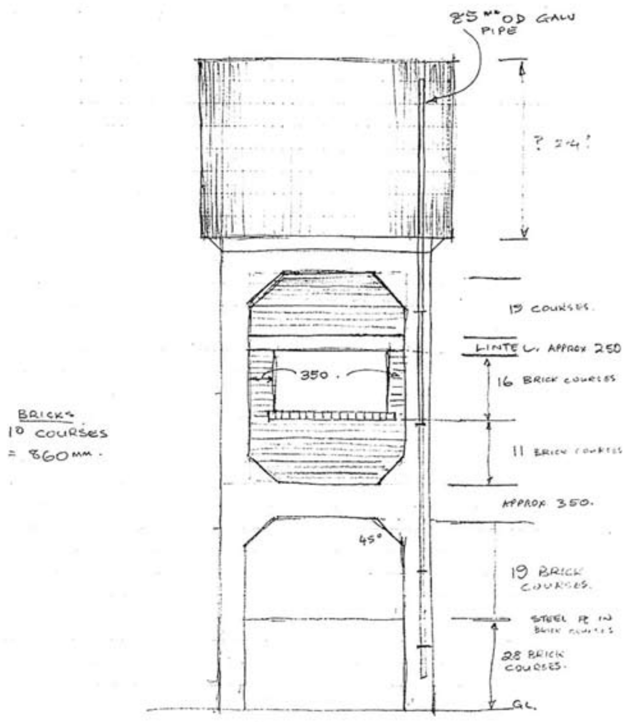



Figure A1.4. South elevation of water tank, Motuihe Island.

## Analysis and report

TABLE A1.1. TABLE OF DEFECTS IDENTIFIED.

| TYPE OF DEFECT | | CAUSE | SEVERITY | RATE | POSSIBLE CONSEQUENCES |
|---|---|---|---|---|---|
| **Reinforced concrete** | | | | | |
| D1 | Crazing | Differential thermal and moisture movement | Mild | Medium | Vulnerable to further corrosion |
| D2 | Pre-spalling cracking | Corroding steel with insufficient concrete cover | Moderate | Medium | Vulnerable to further corrosion |
| D3 | Long edge cracks | Exposure and wetting of corners, subsequent corrosion of steel | Moderate | Medium | Vulnerable to further corrosion |
| D4 | Short edge cracks | Exposure and wetting of corners, subsequent corrosion of steel | Moderate | Medium | Vulnerable to further corrosion |
| D5 | Structural crack | Shearing stress in concrete due to weakening of the structure | Moderate | Slow | Loss of strength |
| D6 | Spalling concrete | Corrosion of steel and resulting expansive forces | Severe | Rapid | Loss of strength, safety hazard, vulnerable to further corrosion |
| D7 | Delamination | Corrosion of steel and resulting expansive forces | Severe | Rapid | Loss of strength, vulnerable to further corrosion, safety hazard |
| D8 | Efflorescence | Sulphates leaching out | Mild | Medium | Unsightly |
| **Brickwork** | | | | | |
| D9 | Weathering | Variable quality of bricks; some poor quality soft bricks | Moderate | Medium | Vulnerable to further corrosion |
| D10 | Mortar joints weathered and disintegrating | Weathering and exposure due to loss of other brickwork and joinery | Moderate | Medium | Vulnerable to further corrosion |
| D11 | Unsupported brickwork | Removal of adjacent brickwork | Severe | Rapid | Loss of strength, safety hazard |
| **Other fabric** | | | | | |
| D12 | Rusting steel bolts | Chloride attack and moisture exposure | Severe | Rapid | Loss of the material and damage to surrounding material |
| D13 | Rusting galvanised steel pipe | Chloride attack and moisture exposure | Severe | Moderate | Deterioration of the material & damage to surrounding material |
| D14 | Delaminating plaster | Differential thermal and moisture movement | Severe | Rapid | Safety hazard |

## Summary of defects and deterioration

The principle cause of damage and deterioration in the structure is corrosion of the reinforcing steel, resulting in spalling of the concrete. Brick masonry panels have been removed from the base and original joinery has been removed from external openings. Repairs are required to stabilise the structure, which is now in poor condition.

The deterioration is due to chloride attack and weathering by the aggressive sea environment. There is generally insufficient concrete cover of the steel reinforcing to provide it with adequate protection. The use of the tower to store salt water means that it would have been continuously exposed to chlorides during its working life. Although no measurement has been taken, the structure is more than likely to have a very high chloride content. The loss of the brickwork from the base and removal of the external joinery has exacerbated the problems by exposing the structure to weathering.

In its current state (July 1999), the condition of the structure can be expected to deteriorate rapidly in the absence of any intervention. The process of corrosion is well advanced and is accompanied by loss of strength as well as loss of concrete surface, i.e. loss of both tensile and compressive strength.

This will ultimately result in the deterioration of the structure to a point where it has to be either completely reconstructed or demolished.

Identified defects and deterioration are analysed in Table A1.1 according to type, cause, degree, rate of activity, and possible consequences.

## Recommended strategies

The following repair strategies are recommended for the repair of the water tower. These are intended to ensure the continued survival of the structure and to make it safe for public access. The recommended measures should arrest its present decline but are not intended to restore its original function of water storage.

1. Spalling and loose concrete should be removed back to sound concrete.
2. Loose bricks should be removed for reuse (unless severely weathered).
3. A protected outlet should be designed and made to ensure that the water tank is always drained and does not accidentally store water.
4. The corroded steel should be cleaned back to clean metal and sealed with a suitable epoxy coating.
5. Chloride extraction should be undertaken to remove the chloride ions from the structure.
6. The structure should be checked by a structural engineer during this process to ensure that the steel and concrete and the structure as a whole are still sufficiently strong to be safe and carry their own weight (but not that of a water load).
7. Previously removed and damaged brickwork should be replaced to match the existing brickwork as closely as possible.
8. Damaged and weathered mortar joints should be repaired with material to match the original.
9. The spalled concrete should be replaced with Portland cement concrete that matches the original as closely as possible in strength, permeability and appearance. Use of a low water to cement ratio and thorough curing will ensure minimum shrinkage and thus greater adherence and less cracking. Consideration should be given to careful use of admixtures and a bonding agent to aid in this process of repair.
10. Efflorescence should be scrubbed off with water.
11. Consideration should be given to replacing the lost joinery, as this will considerably lessen the exposure of the structure.
12. Once the concrete has been repaired, a surface treatment can be applied that will provide chloride protection. This must be breathable, i.e. be water vapour permeable not water permeable, to ensure that moisture is not trapped inside, but should ensure that water runs off the surface of the structure rather than soaking in.
13. Following on from this, there should be interpretation of the structure and the site and its historical context.
14. A system of maintenance and monitoring should take place on a 5-year basis, as no process of repair can expect to solve all future problems, especially for reinforced concrete in an aggressive environment. As part of this process, the condition of the structure should be reviewed and minor maintenance and repairs should be undertaken.

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