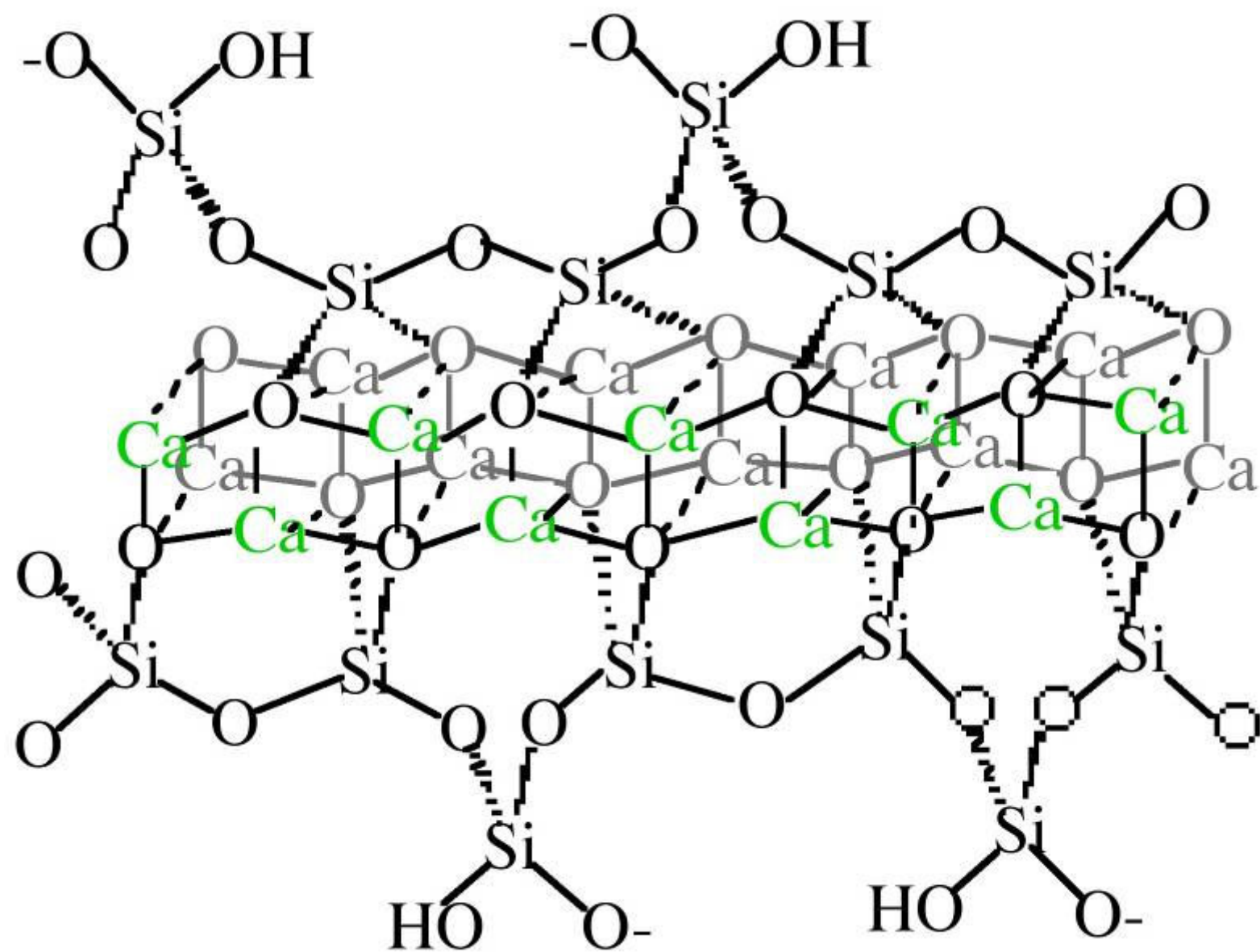


The most widely used cement is portland cement. The four major Bogue clinker phases present in portland cement are tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), and tetracalcium aluminoferrite (C_4AF); the clinker is ground with gypsum ($C\ H_2$). The formulae in parentheses use the standard cement chemistry abbreviations: C = CaO, S = SiO_2 , A = Al_2O_3 , F = Fe_2O_3 , \bar{S} = SO_3 , and H = H_2O . Densities and molar volumes for all phases relevant to our models, taken from the cement literature (Lu *et al* 1993, Mindess and Young 1981, Young and Hansen 1987), are given in table 1.

Table 1: Densities and molar volumes of cementitious materials

Compound Name	Compound Formula	Density (g cm ⁻³)	Molar Volume (cm ³ mol ⁻¹)
Tricalcium silicate	C_3S	3.21	71
Dicalcium silicate	C_2S	3.28	52.4
Tricalcium aluminate	C_3A	3.03	89.1
Tetracalcium aluminoferrite	C_4AF	3.73	128
Gypsum	CH_2	2.32	74.2
Calcium silicate hydrate	$C_{1.7}SH_{1.1}$	1.85	124
Pozzolanic C-S-H	$C_{1.1}SH_{2.1}$	1.97	81
Calcium hydroxide	CH	2.24	33.1
Ettringite	$C_6A_3H_{32}$	1.75	715
Monosulphate	C_3AH_{12}	1.99	313
Hydrogarnet	C_3AH_6	2.52	150
Iron hydroxide	FH_3	2.2	95.2



The Identification and Assessment of Defects, Damage and Decay

John Broomfield

Introduction

There are a number of causes of deterioration in concrete buildings and structures. Even when they are adequately built, properly used and well maintained the environment will affect a structure and components will wear out. The largest single cause of deterioration in reinforced-concrete structures is corrosion of the reinforcing steel. In addition, there are a number of deterioration processes that attack the concrete directly, some from within, such as alkali-silica reactivity, and some from without, such as freeze-thaw damage. Others are related to initial construction problems or subsequent use or abuse of the structure.

This chapter summarises the major causes of defects, damage and decay in concrete buildings and structures. Any attempt to remedy problems must start with a thorough understanding of the cause and extent of the deterioration. As discussed in Chapter 3, it is therefore essential that a detailed investigation is carried out as part of the appraisal process, the results are interpreted, and the repair options fully evaluated to ensure that the right repair option is selected for the building and its owner. This chapter is therefore an essential precursor to Chapter 5, which deals with repair options. The main causes of concrete deterioration are summarised in Fig. 4.1, and these are discussed in detail in the following sections.

Corrosion of steel in concrete by carbonation and chlorides

One of the many fascinating properties of concrete is its relationship with the steel embedded in it. Historically, attempts were made to reinforce concrete with metals such as bronze. The resulting failures were due to the difference in thermal expansion coefficients between the bronze and the concrete. Steel has a similar enough thermal expansion coefficient to concrete to avoid damage. However, steel corrodes in a moist oxygenated atmosphere. Despite its porosity and the natural moisture level of

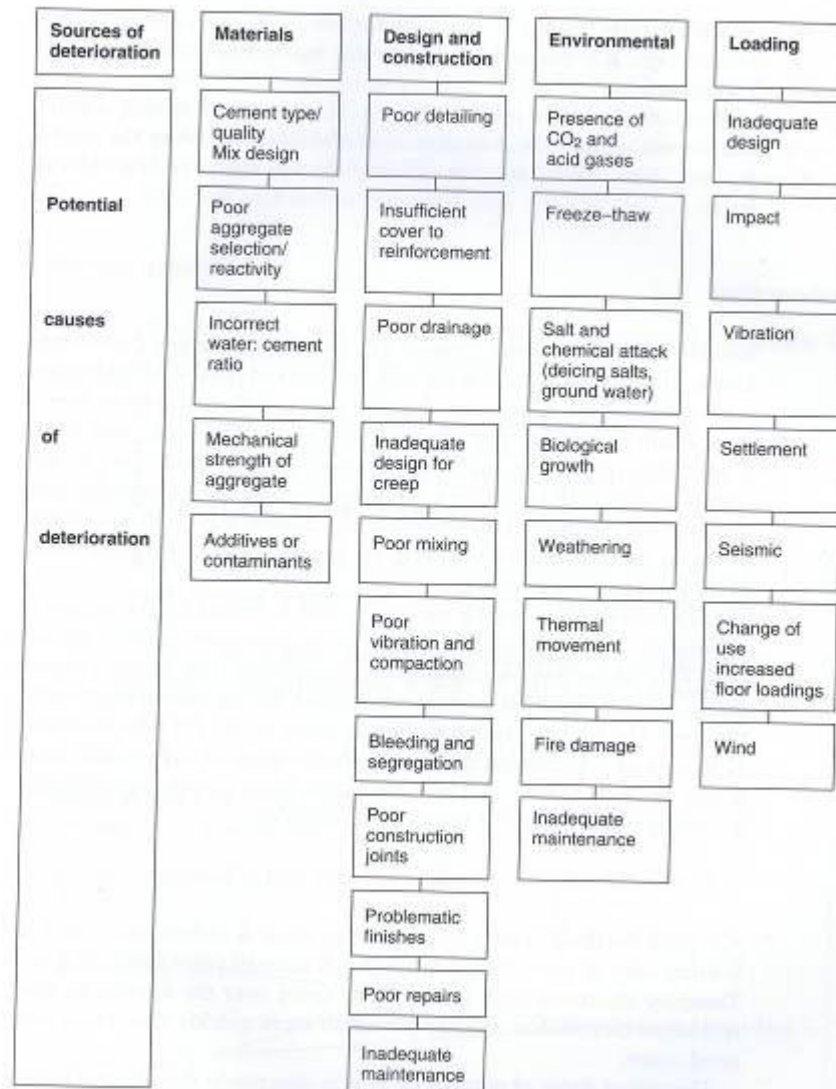


Fig. 4.1 Sources and causes of concrete damage, defects and decay (Susan Macdonald).

concrete exposed to the outdoor atmosphere, steel does not necessarily corrode once it is encased in concrete for reasons discussed in the following section.

There are two major mechanisms for the corrosion of steel in concrete that do not require the degradation of the concrete before the steel is attacked. The first of these is carbonation and the second is chloride attack.

Carbonation

Reinforcement corrosion is prevented by the alkali content of the concrete. During the hydration process calcium, sodium and potassium hydroxides are formed, which dissolve in the pore water of the concrete to form a very alkaline solution of around pH 12–13.5. At this level, steel forms a very thin, protective oxide known as a passive layer. This is self-sustaining and maintaining; it is far better than synthetic or metallic coatings that deteriorate or are consumed. The passive layer will sustain and maintain itself indefinitely as long as the alkalinity stays above about pH 11 without contamination.

Carbonation is eventually inevitable, and is caused by the ingress of atmospheric carbon dioxide reacting with the pore water to form carbonic acid. This neutralises the alkalinity in the concrete. This occurs progressively, and a carbonation front moves through the concrete until it reaches the steel. The passive layer then breaks down as the pH falls from over 12 to around 8. Corrosion can start in the presence of oxygen and water as the pH falls below 11. The carbonation front moves approximately according to the following parabolic relationship:

$$\text{Carbonation depth} = \text{Constant} \times \text{Square root of time}$$

A typical Portland cement concrete may show a carbonation depth of 5–8 mm after 10 years, rising to 10–15 mm after 50 years (BRE, 2000 (a)). Therefore structures with low concrete cover over the reinforcing steel will show carbonation-induced corrosion more quickly than those with good cover.

The rate of decay of reinforcing steel in concrete is also affected by the concrete quality. Concretes made with a high water to cementitious ratio and with a low cementitious content will carbonate more quickly than well-made concretes because they are more porous and have lower reserves of alkali to resist the neutralisation process. For concretes with pulverised fuel ash or other cement replacement materials, the drop of alkaline reserves is usually balanced by the increase in concrete quality

for an equivalent Portland cement, except at high replacement levels in dry conditions (BRE, 2000 (a)).

The rate of carbonation is also affected by environmental conditions. Carbonation is more rapid in fairly dry and wet/dry cycling environments. It may therefore occur more rapidly in bathrooms and kitchens in blocks of flats, and in multistorey car parks where the carbon dioxide levels are high due to exhaust fumes.

Chloride attack

The second major cause of reinforcement corrosion is chloride attack. This is usually due to one of the following causes:

- de-icing salt ingress from roads and vehicles;
- sea-salt ingress in marine environments;
- cast-in salt from contaminated mix components;
- cast-in calcium chloride as a set accelerator.

A certain level of chloride is needed for corrosion to occur. Figure 4.2 illustrates the relationship between chloride level, carbonation and corrosion risk.

Once the chloride level at the reinforcement exceeds 0.4% by weight of cement (approximately 0.06% or 600 p.p.m. by weight of sample

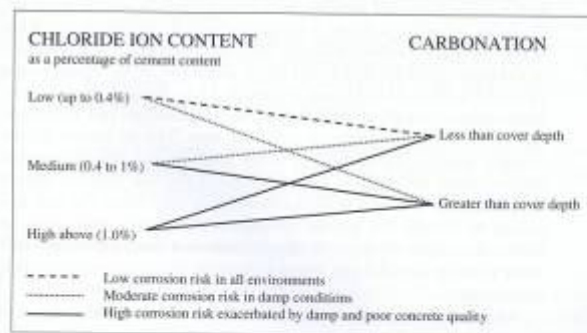


Fig. 4.2 Risk of corrosion in relation to concrete analysis (reproduced from BRE Digest 264, 1982).

assuming 15% cement content), there is a significant risk of corrosion, especially in the presence of moisture. Obviously, if cast-in chlorides exceed 0.4%, then the corrosion risk rises (see BRE, 2000 (a)).

For chlorides that are diffusing into the concrete (as a result of salty sea spray or de-icing salts, for example), it can be a useful approximation to calculate the progress of a 0.4% chloride by weight cement-corrosion threshold progressing through the concrete at a parabolic rate comparable to the carbonation rate equation above,

$$\text{Chloride threshold progress rate} = \text{Constant} \times \text{Square root of time}$$

The use of this approximation, along with sampling and interpretation, is discussed in the section on sampling below.

As with carbonation, chloride-ingress rates are a function of concrete quality and environment. For concrete with low reinforcement cover, and particularly for poor-quality concrete, chlorides can be transported rapidly by wetting and drying absorption and by capillary action that almost sucks the chloride-laden water into the concrete. The water then evaporates and leaves the salt behind. In good-quality concrete with good cover to the reinforcement, diffusion processes predominate.

The corrosion process

Regardless of the cause of corrosion, once the steel's passive-layer protection is lost, corrosion proceeds by the mechanism illustrated in Fig. 4.3. Corrosion of steel in concrete is an electrochemical reaction in which the major constituent of steel (iron) goes into solution as iron ions with a flow of electrons (electrical flow). This site is called the anode. Electrons are produced in this self-sustaining process and flow through the reinforcement towards cathodic sites where they react with oxygen and water from outside to produce additional hydroxyl ions. This is known as the cathodic reaction. As can be seen in the diagram, the cathodic reaction requires water and oxygen. The initial anodic reaction does not require anything, once the steel is depassivated, it is only when the iron has reacted to become the soluble ferrous ion that it will react with the hydroxide ion (the alkalinity in the concrete), and then with oxygen and water to create the solid rust whose volume increase will crack and spall the concrete.

The fact that oxygen is not required at the anode is important because the exclusion of oxygen from anodic areas without stifling the cathodic reaction will lead to dissolution of the reinforcement rather than cracking

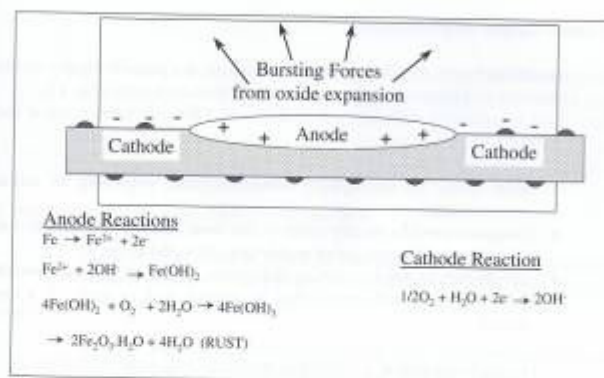


Fig. 4.3 The corrosion process for steel in concrete.

and spalling of the concrete. This can happen in local saturation conditions where the concrete is very wet and therefore conductive enough to allow good separation between anodes and cathodes.

The ingredients for corrosion are therefore:

- carbonation or sufficient chloride at reinforcement depth to depassivate the steel;
- oxygen to fuel the cathodic reaction and to create the expansive oxide;
- water to fuel the cathodic reaction and to create the expansive oxide;
- concrete of low enough resistivity to allow the electrochemical anode and cathode reactions to proceed.

These ingredients, along with the electrical nature of the reactions, can therefore be used to assess the corrosion condition, as described in the section on condition survey techniques below.

Design and construction defects

The performance of reinforced concrete can be severely reduced by poor design and construction techniques. These may cause reinforcement corrosion or degradation of the concrete itself, which in turn may lead to reinforcement corrosion.

Poor cover to the reinforcement

Insufficient concrete cover to the reinforcement is a major influence on the durability of reinforced-concrete buildings and structures (Fig. 4.4).

A number of problems, particularly with older structures, occur at the design stage, such as:

- older codes do not specify adequate cover, especially in saline environments;
- designers used to specify cover to the main steel, which meant that there was inadequate cover to stirrups, clips and so on;
- details such as drips, grooving of surfaces, and so on, reduced overall cover, often to vulnerable steel at corners and in areas of water run-off.

During construction a number of problems may arise, including:

- detailing that makes it difficult to achieve the specified cover;
- incorrect reinforcement placing;
- movement of reinforcement within shutters from the specified cover.

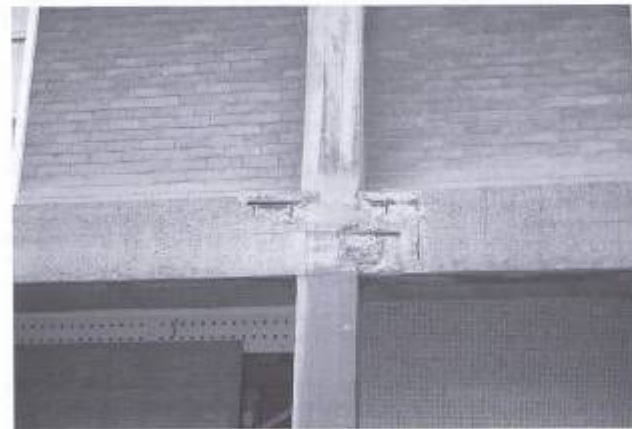


Fig. 4.4 Insufficient cover to reinforcement at Parkhill flats, Sheffield, is one of the most common causes of premature corrosion-induced concrete decay (photo Susan Macdonald).

Poor consolidation leading to honeycombing and voids

Poor consolidation of the concrete during pouring leaves honeycombing and voids in the concrete. These are frequently visible at corners and slab ends, where the cement paste does not completely surround the larger aggregate particles. Problems can occur over congested steel, where it is difficult to ensure that the concrete flows into all the interstitial spaces.

Concrete constituents and manufacture

There are a number of problems that can occur with the concrete mix at either the design or the execution stage. These are discussed in detail later in this chapter, and include:

- high water to cementitious products ratio—this leads to a porous concrete susceptible to carbonation and chloride ingress;
- cast-in chlorides—until the mid-1980s, calcium chloride set accelerator was considered to be a useful and safe admixture, as chlorides were considered to be bound into the concrete; similarly, seawater was used during construction on marine projects, a practice we now know to be problematic. Accidental inclusion of chlorides also occurs due to poorly washed mix constituents and contaminated water supplies;
- inadequate slump—the reverse of high water to cementitious product ratio, with inadequate superplasticiser giving rise to poor consolidation resulting in honeycombing and voids;
- alkali-aggregate reaction—where the aggregate reacts to the alkalinity of the cement.

Creep

Creep is caused by water being squeezed from the pores of the concrete owing to the sustained load of the concrete itself. Deformation due to creep is time-dependent, and it may not become apparent until some months after a structure has been completed. Allowance for deflection due to creep is made at the design stage. Where inadequate allowance has been made for creep, finishes may be affected by cracking. Openings may deflect, causing doors or windows to jam, for example.

Concrete degradation

Concrete is a relatively durable material, but it can be severely weakened by poor manufacture, the inclusion of damaging constituents or aggres-

sive environments. As mentioned above, there are a number of causes of degradation of the concrete matrix.

Alkali-aggregate reactivity

As described previously, concrete pore water is highly alkaline. Unfortunately, some aggregates used to make concrete react with the alkalinity to form products that swell and damage the concrete.

The most common alkali-aggregate reaction is an alkali-silica reaction, known as ASR. Soluble silicates in the aggregates react and form silica gels. These gels absorb water and expand. The result is a 'map cracking' effect and efflorescence of the gel, as shown in Fig. 4.5.

Many aggregates exhibit ASR to a greater or lesser extent when examined by petrographic analysis under a microscope. A more limited number show serious problems which are now well characterised in terms of type and source. Frequently, ASR will occur on a structure or part of a structure, the susceptible aggregates will react and then the situation will stabilise. The problem is frequently one of appearance rather than anything else. In a series of over 100 structures with ASR in the UK, typically 0.03 mm/m/year to 0.3 mm/m/year expansion occurred over 20 years (Wood, 1990). It may be possible to slow ASR by



Fig. 4.5 Map cracking due to an alkali-silica reaction.

reducing or eliminating moisture either by deflecting the run-down, or by the application of coatings or sealers.

Sulfate attack

Sulfates of sodium, calcium, potassium and aluminium are found in groundwater and soils and can cause degradation of the concrete matrix by expansive attack of the calcium hydroxide and calcium aluminates in the concrete. Wet/dry cycling causes salts to be accumulated on the concrete surface, resulting in degradation. Delayed ettringite formation, and the recently discovered problem of thurmasite attack of concrete, are also forms of sulphate attack. More than 0.1% water-soluble sulfate in soil or 150 p.p.m. in water is moderate exposure to sulfate attack. More than 2% in water or 10000 p.p.m. in soil is severe exposure. A high-quality dense, blended cement concrete gives good sulfate resistance. Low C_3A content cements have the disadvantage of low resistance to chloride ingress, so in cases where the sulfates are from marine exposure, sulfate-resistant Portland cement (ASTM Type II) may accelerate chloride-induced corrosion.

High-alumina cement concretes

High-alumina cement (HAC) was used extensively in the 1960s and 1970s to achieve very high early strength concrete. HAC also has a higher level of resistance to acids and sulfates. Under certain conditions during its curing (high water:cement ratio and high temperatures during curing) and particular environmental conditions after construction (high temperatures and/or high humidity levels), it suffers from a chemical (crystal) change and severe loss of strength and porosity. The cement is then attacked by some chemicals, such as calcium sulfate found in gypsum plasters. This has resulted in a number of serious structural failures. A major programme of identification of HAC structures has been undertaken in the UK and most other countries where it was used; HAC beams and columns have been replaced, supported or are carefully monitored. HAC also has very low reserves of alkali, so it carbonates very easily.

Environmental influences

In addition to the damage caused to concrete as a result of exposure to environmental agents such as carbon dioxide and acid gases, there are a number of other environmental factors that can cause deterioration.

Weathering

Staining

Water-staining of unpainted concrete is a major problem in the UK. The porosity and water-absorption characteristics of concrete seem to make it more susceptible than brick and stone to this type of soiling. Concrete can be cleaned like any natural stone or brickwork, and similarly removing surface laitance can make it more susceptible to future staining. Cleaning is discussed in detail in Chapter 6.

Erosion

Continuous water run-down, especially of water containing suspended solids, will erode concrete with time. Salt water and other aggressive solutions will etch concrete.

Efflorescence

Efflorescence can occur due to ASR, water run-off, or water running through slabs and carrying away the soluble calcium. Figure 4.6 shows an extreme case of a car park with stalactites and stalagmites forming where water runs through an unmaintained suspended slab.

Freeze-thaw damage

Freeze-thaw damage occurs where water accumulates in cracks, voids or pores of the concrete, and then freezes quickly enough so that the expansion cracks the concrete. Air-entrainment produces pores and small voids in the concrete of a size to avoid freeze-thaw. Older structures (that may not have been well air-entrained) and those in a severe heating/cooling environment will suffer from the scaling away of the concrete surface due to freeze-thaw damage.

Structural damage

Structural damage can result from;

- inadequate design or construction;
- settlement or other ground movement;
- overloading or change of use;
- fire damage;



Fig. 4.6(a) Poor maintenance of this car park has led to the formation of a stagnant water where the inadequate drainage keeps water off cars but does not cure or control leakage from the floor above.

- impact damage;
- seismic damage;
- wind damage.

These are usually easily identified by a qualified engineer. There are well-proven methods to rectify these problems. The importance of a structural appraisal in determining a concrete building's suitability for use is discussed in Chapter 3.

In most Western countries, there are usually sufficient resources and expertise to prevent corrosion from becoming a structural problem. However, the removal of the cover concrete by the expansive growth of oxides will reduce the bond between steel and concrete, which could

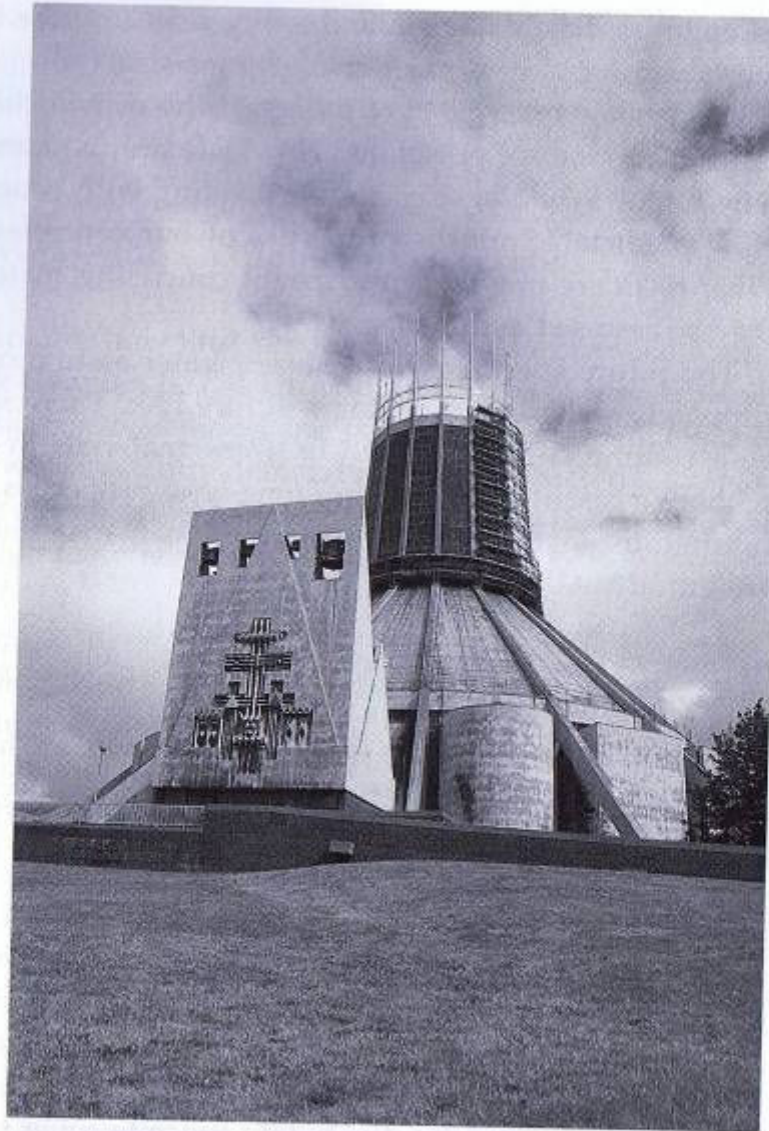


Fig. 7.4 Christ the King Cathedral, Liverpool, designed by Sir Frederick Gibberd and completed in 1967, was built to last 500 years. A major programme of repair in the 1990s addressed a series of problems, including those relating to the mosaic cladding on the concrete ribs (photo Susan Macdonald).





















