

# Diagnosing and repairing carbonation in concrete structures

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*Toby Ware has been building surveying for eight years following a passion for construction, while assisting on building sites during his spare time. Toby was recruited to Naylors to establish a building consultancy and project management department and there are now four members of staff serving this discipline. He has a claim to fame of providing professional building surveying advice on a popular BBC television programme.*

### ABSTRACT

*This paper concentrates on the carbonation of concrete, but also provides a brief synopsis of varying defects in concrete when used as a building material. It outlines the different defects that can arise with concrete, discusses the cause of these defects, and puts forward industry-recommended remedial action. It also uses live case study examples of the solutions to prolonging the life expectancy of external concrete facades.*

**Keywords:** concrete, carbonation, HAC, corrosion, aggregates, curing, admix, passive layer

### HISTORY OF CONCRETE

The word concrete comes from the Latin word *concretus*, which means compact or condensed. Concrete was an important construction material in Roman times and was widely used in their buildings. There is, however, evidence that concrete was used well before the Roman era, with suggestions of it having been laid in 5600 BC. It became

a scarce and a relatively forgotten material after the collapse of the Roman empire, until the technology was reinvented by the use of a new form of cement, Portland cement, which is how we know it today.

The Romans used ‘pozzolanic’ cement, where they added volcanic ash to a normal lime-based concrete, producing a much stronger material. Portland cement is an artificial cement, which contains similar materials and is made by heating limestone, a source of calcium, with clay and grinding this product (called ‘clinker’) with a source of sulphate, most commonly gypsum. The burning process was required to change the chemical properties of the materials and create an even stronger cement.

In 1756, British engineer, John Smeaton made the first modern concrete (hydraulic cement) by adding pebbles as a coarse aggregate and mixing powdered brick into the cement. Portland cement was invented in 1824 by Joseph Aspdin, who was an English masonry worker. Reinforced concrete was invented in 1849 by Joseph Monier, who received a patent in 1867.

An example where Roman concrete has been used and still stands today is in the concrete dome of the Roman Pantheon. It was rebuilt in 126 AD and is still the largest unreinforced concrete dome in the world. The height to the oculus and the diameter of the interior circle are the same, 43.3m (142ft).

Concrete is now extensively used throughout the world on a large variety of different constructions, including the world’s

tallest building, Burj Khalifa's in Dubai. It is constructed of reinforced concrete and in May 2008, it was pumped to a then world record height of 606m (1,988ft), the 156th floor. Construction used 330,000m<sup>3</sup> (431,600 cu yd) of concrete and 55,000 tonnes of steel rebar. The foundations are constructed of a high density and low permeability concrete.

### WHY USE CONCRETE?

Concrete has relatively high compressive strength, but much lower tensile strength, ie it can take a great weight crushing down on it but does not perform so well when pulled or deflected. For this reason, it is usually reinforced with materials that are strong in tension, often steel, and it can then be used in a multitude of applications.

The main factors when considering concrete are:

- *Adaptable:* The proportions of the natural ingredients can be altered, or different materials used in the mix to enable it to be manufactured to a variety of specifications to suit all locations, conditions and applications.
- *Architectural:* It can be used as an architectural feature, either left in its raw form or finished to any specification. It also provides an excellent framework for a variety of surface finishes, which can be applied when the concrete is wet or once it has hardened.
- *Styled:* The fluidity of concrete allows it to be moulded into almost any shape conceivable. By using appropriate formwork, bespoke designs and architectural styles can be created. These can be used as the finished surface, which will reduce the need for further fixings.
- *Durable:* Concrete is extremely durable and it can be serviceable for hundreds of years if it is well designed and well placed. It is therefore imperative that the minimum

cover is met, attention to detail and care during the execution of the works achieved, and sufficient time is given for it to cure. This also reduces the overall maintenance requirements and ongoing repair costs.

- *Environmentally-friendly:* Some may not think so but concrete is actually environmentally-friendly right from its manufacture through to its final use, and even beyond this. It contains naturally occurring materials, does not produce any emissions, and needs no toxic preservatives. Designers and end users can utilise its thermal mass and omit the need to install air conditioning units, and on some occasions even heating systems. Concrete can also be recycled when a building is demolished and an ever-increasing amount of recycled materials are used in its manufacture.
- *Fire-resistant:* Concrete provides the best fire resistance of any building material. It does not need additional fire protection, it does not burn and cannot be set on fire. It does not emit any toxic fumes or smoke, or drip molten particles when exposed to fire. Concrete receives the highest fire resistance classification (class A1) under EN 13501-1.
- *Sound protection:* Concrete's inherent properties contribute to good sound insulation which is required to give adequate levels of privacy to the occupiers.

### CARBONATION OF CONCRETE

As soon as concrete is poured, it is under attack from pollutants in the atmosphere and naturally occurring gases such as carbon monoxide. It can also be damaged by many processes such as collisions with vehicles and from the freeze thaw action of trapped water.

#### Concrete's passive layer

Concrete is an alkaline, and when it has just been poured its alkalinity approaches pH 13.

It is this high alkalinity that protects the steel from oxygen and water by forming a thin oxide layer on the steel, thus preventing the metal atoms from dissolving, ie corroding. This protection is known as the passive layer.

This passive layer does not actually stop corrosion; it reduces the corrosion rate to an insignificant level. For steel in concrete, the passive corrosion rate is typically 0.1µm per year. Without the passive film, the steel would corrode at rates at least 1,000 times higher.

Rust has a lower density than metal, so it expands as it forms. As it does, it cracks and damages the surrounding concrete, further damaging the surrounding passive layer.

Corrosion can still occur however, when the passive layer breaks down and becomes compromised. The deterioration of the protection occurs when the alkalinity of the concrete is reduced or when the chloride concentration in concrete is increased to a certain level. This is mainly caused by the natural process of the gases in the air.

**Carbonation process**

The carbonation of concrete (Figure 1) is one of the main defects in concrete, causing the reinforcement to corrode. Along with

the breakdown of the passive layer, oxygen and moisture are the other components required for corrosion of embedded steel.

Carbon dioxide (CO<sub>2</sub>), which is a natural gas present in the air, and sulphur dioxide (SO<sub>2</sub>), which is increased by industrial production, combine with the moisture (CO<sub>2</sub>) in the atmosphere and react with the calcium hydroxide in the concrete producing calcium carbonate and calcium sulphate (gypsum).

This chemical process and the reaction of the material attacks the concrete and reduces the natural alkalinity. The layer of affected concrete is known as the carbonated layer, and when the steel reinforcement falls within this, it loses its passive layer. The oxygen and moisture then penetrate the concrete and react with the steel causing it to corrode.

In actual practice, CO<sub>2</sub> present in the atmosphere, permeates into concrete and carbonates it naturally, reducing the alkalinity of the concrete. The pH value of pore water in the hardened cement paste, which was around pH 13, will be reduced to around pH 9.0. When all the Ca(OH)<sub>2</sub> has become carbonated, the pH value will reduce to about pH 8.3, at which level the passive film on the steel is not stable. The loss of the passivity usually occurs around pH 11.

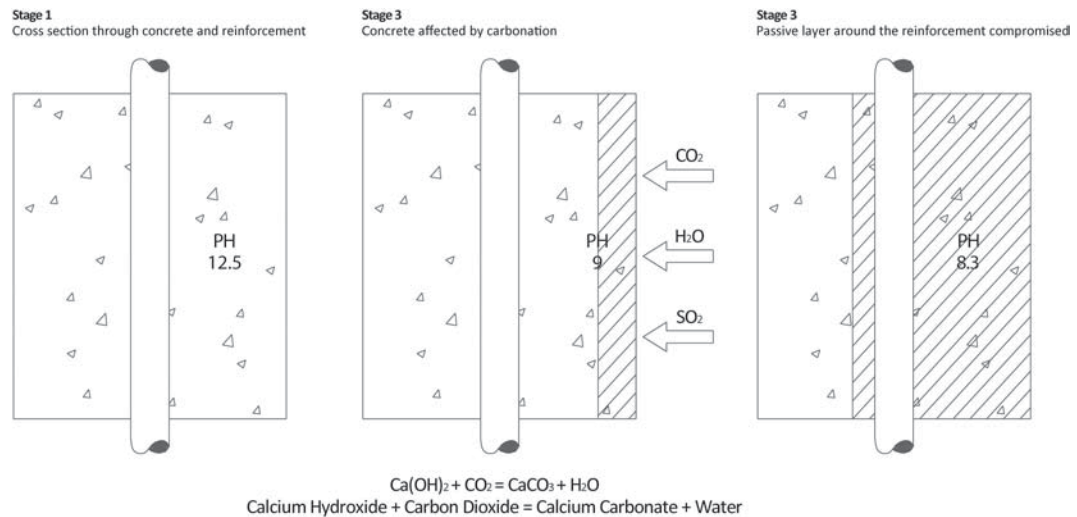


Figure 1: The carbonation of concrete

Carbonation is overall a slow process, with it proceeding in high-quality concrete at a rate up to 1.0mm (0.04 in) per year. The rate of carbonation can vary however, and depends on the following factors of the concrete:

- (1) the level of pore water, ie relative humidity;
- (2) grade of concrete;
- (3) permeability of concrete;
- (4) whether the concrete is protected or not;
- (5) depth of cover; and
- (6) time.

Carbonation is dependent on the relative humidity of the concrete. The highest rates of carbonation occur when the relative humidity is maintained between 50 per cent and 75 per cent. Below 25 per cent relative humidity, the degree of carbonation that takes place is considered insignificant. Above 75 per cent relative humidity, moisture in the pores restricts CO<sub>2</sub> penetration. Carbonation-induced corrosion often occurs on areas of building facades exposed to rainfall, shaded from sunlight, and having low concrete cover over the reinforcing steel.

### Diagnosing carbonation

The first time that carbonation is evident is usually when the concrete around the reinforcement spalls and cracks. Over time this will worsen and expose the corroded reinforcement.

If the depth of carbonation needs to be established, then a simple method to test this is to treat the concrete with phenolphthalein. Phenolphthalein comes in powder form, and will need to be dissolved in alcohol for use in this test.

In order to undertake the test, a section of concrete should be broken away and the fresh surface sprayed with the solution. Alternatively, it can be applied to split cores, the powder from drill holes, or allowed to fall on indicator-impregnated paper.

Phenolphthalein is an acid base indicator, which makes it extremely useful for testing for signs of carbonation. The solution will turn bright pink if it interacts with an alkaline and will even show up to a pH 9.5. As unaffected concrete has a high pH, it will turn pink, but if concrete is carbonated, it will remain uncoloured. It should be noted that the pink colour indicates that enough Ca(OH)<sub>2</sub> is present but it may have been carbonated to a lesser extent.

The test is covered by BS EN 14630, 'Products and systems for the protection and repair of concrete structures. Test methods. Determination of carbonation depth in hardened concrete by the phenolphthalein method'.

### Repairing carbonation

The Building Research Establishment's Digest 444, Part 3 and the Concrete Society's Technical Report Number 38 provide guidance on the appropriate repairs, and these should be closely followed when preparing specifications. A brief synopsis of their requirements is as follows, and these steps should be undertaken to provide a satisfactory result:

- Undertake hammer test to establish all loose areas of concrete.
- Hack off loose concrete from around the exposed steel bars.
- Grit blast to remove corrosion and other deposits from the exposed steel reinforcement including hidden faces, to the back of the steel bars, and to intersections of bars.
- Apply a proprietary bar primer to the surface of the reinforcement. This could either be alkali based; encapsulating, such as epoxy resin; or sacrificial, normally zinc-rich paints.
- Patch repair areas of concrete using a cementitious material and sand, and a polymer dispersion.

### Protecting concrete in the future

A long term solution to inhibit further carbonation would be to restrict the entry of

carbon dioxide by applying a coating to the concrete that will act as a protective barrier. The coating should prevent the ingress of liquid water, but allow water vapour to pass through. There are various products on the market specifically designed for this purpose.

The necessary surface preparation has to be undertaken, which will usually consist of cleaning the surface back to a sound finish. The coating treatment should then be checked for its compatibility with the concrete, and the number of coats and total thickness required also considered.

It also provides the opportunity to provide a facelift to the building, and these systems usually carry a guarantee with a recoating required at given times.

## **OVERVIEW OF OTHER DEFECTS TO BE AWARE OF**

### **Chlorides**

Calcium chloride was once used as an admixture in the manufacturing process of concrete. It was included in the mix, as it would promote rapid set-up of the concrete and it was believed to prevent freezing. During the 1960s and 1970s magnesite, a chloride-rich carbonate mineral was used as a floor screed providing sound attenuation and a level surface. When this chemical reacts with moisture, it produces a weak hydrochloric acid.

In high enough concentration, the chloride breaks down the passive film in localised areas rather than the widespread deterioration seen in carbonation. This results in rapid corrosion of the metal at the anode, which leads to the formation of a pit in the bar surface and significant loss of cross-sectional area. There are occasions where the bar is seen to be completely eaten through.

Chlorides from de-icing salts can migrate into the capillaries of the concrete and affect

the reinforcement. The de-icing slats are probably one of the primary causes of the failure of the reinforcement in highway constructions.

Seawater can also migrate into the capillaries, and it was once used to mix the concrete. This had an adverse effect and it is often why more serious corrosion occurs at the coast. It is therefore important that fresh water or potable water is used; the coarse and fine aggregates do not contain chlorides; and admixtures that contain chlorides are not used.

Cathode protection, along with epoxy-coated reinforcing bars can be used to mitigate the problem. Cathode protection is an electronic process that makes the metal structure of the building more negative in order to decrease corrosion. When a concrete mix is properly designed from the outset and given sufficient time to cure, it will effectively become impervious to the effects of de-icing salts.

### **Alkali silica reaction**

This reaction and subsequent defect is often referred to as concrete cancer. It occurs on large concrete structures without the presence of reinforcement bars.

The situation occurs when elements sometimes present in the aggregates react with the cement pore solution to form a highly expansive solution that causes localised swelling. The three conditions required for this reaction are:

- (1) aggregate containing an alkali-reactive constituent (amorphous silica);
- (2) sufficient availability of hydroxyl ions in the pour solution;
- (3) sufficient moisture, above 75 per cent relative humidity within the concrete.

Therefore, to prevent this from occurring, the alkali metal content of the cement and reactive silica content of the aggregate should be limited during its manufacture. Alternatively,

admixes can be included to neutralise the excessive alkalinity of cement. Care should be taken though, so as not to induce the acceleration of carbonation if reinforcement is present.

### **Conversion of high alumina cement**

This type of concrete was manufactured to resist chemical attack from weak acids and sulphates. It also developed high early strength. It was relatively expensive to produce, but this was offset by its quick manufacturing process. It was mainly used for precast pre-stressed components such as concrete roof beams.

It was, however, banned in 1976 for structural use, as it undertakes a mineralogical change whereby the concrete increases in porosity, which in turn results in a loss of strength and a reduction in resistance to chemical attack. This process is known as the conversion of the concrete, and the higher the temperature during the casting of the concrete, the more quickly conversion takes place.

There have been collapses of some structures using high alumina cement, so it is important to diagnose this through identification, strength assessment and durability assessment.

### **Sulphates**

Sufficient concentrations of sulphates in the soil, groundwater or hardcore can react with the cement in concrete to form expansive products that can be up to twice the volume of the concrete. This reaction causes significant heave to ground floor slabs and can also cause structural damage to the main walls by pushing them out. Eventually the concrete may disintegrate.

The process can be prohibited by the inclusion of an adequate damp-proof membrane between the fill and slab. Hardcore containing sulphates is now banned from use below floor slabs, which also reduces the risk.

A chemical analysis of soil borings should be undertaken during the design phase of

any project involving concrete in contact with the soil to check for the presence of sulphates. If the concentrations are found to be aggressive, various protective coatings can be used.

## **INNOVATION IN CONCRETE TECHNOLOGY**

There have been many innovations in concrete over the years, which have changed its form and improved its properties. As noted above, some of these have not been successful, with the defects not becoming evident until later in life.

Some of the more recent concrete advances are noted below.

### **Self-compacting concrete**

Self-compacting concrete does what it says and negates the need to use a compacting vibrator machine. This means it can be used where there is limited or no access and in complex shapes of formwork that may otherwise be impossible to cast, giving a far superior surface than conventional concrete.

### **Insulating concrete formwork**

These are large modular units, which interlock to form the basis of the shell of a building. They are then filled with concrete and remain in place once it has cured. They are extremely energy-efficient, and the system is becoming ever more popular in low-rise buildings.

### **Jointless concrete**

Technically, some expansion joints have to be formed to allow the concrete to flex. This type of concrete is predominantly used to provide smooth finished floors. Small bits of fibreglass can be added to the concrete mix to toughen the floor and reduce the number of expansion joints needed.

As buildings are getting ever taller, concrete now has to withstand the extreme pressures of the weight of itself bearing down from above. Special mixes can be made, with

every batch put through checks to ensure it is consistent and can withstand the pressures.

An additive is not always required, as there can be simple solutions that ensure the concrete sets correctly. When constructing in countries where the temperature can reach 50°C (122°F) ice can be added, and it is usually poured during the night when the air is cooler and humidity higher. A cooler concrete mixture cures evenly throughout and is therefore less likely to set too quickly and crack.

### **CONCLUSION/ONGOING ISSUES WITH CONCRETE**

Concrete has advanced somewhat since Roman times, with poor practices in earlier

concrete now realised. This is definitely something keeping the building surveyor busy in terms of regular maintenance and complete repairs.

Although concrete is a major contributor to greenhouse gases, it is now seen to be an ideal building product, as it insulates against the cold and retains the heat. More and more buildings are therefore constructed from concrete, and it is becoming ever-increasingly popular with designers and end users.

The other important factor is that structures made of concrete can have a long service life as long as it is designed correctly, placed well, and allowed to cure properly.