

Carbonation of Concrete: Measurement and Repair

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Abstract To extend the service life of concrete structures, measures against the damage from carbonation are often sought. However, it becomes progressively difficult to guard the existing concrete as the structures have aged and their porosities may be mixed and varied. This work aims to provide the state of the art concerning the carbonation process of concrete and the methods available for the determination of the carbonation depth, assessing the quality of the concrete, and repairing the damaged concrete. Information is gathered from an extensive literature study and from interviews with experts in the field. Interaction with research students and researchers working in the field of carbonation of concrete has also been of value. The phenolphthalein test and the indicator method were adapted to determine the carbonation front of the concrete. The extent of carbonation was evaluated using concrete core extraction method and a cover meter which can give an indication of the depth of concrete cover over reinforcement and a rough estimation of the diameter of steel present. Since the carbonation process is affected by a myriad of variables, this study focuses solely on the most systematic methods available for determining the carbonation depth and the influence factors on reinforcement corrosion such as water-cement ratio (W/C), composition of the concrete, the temperature, the relative humidity and the resistivity. Test results have shown that the carbonation is the principal cause of reinforcement corrosion in many concrete structures. Indeed, the measure of the depth of carbonation and thus detecting its presence has very important repercussions on the repair method.

Keywords Concrete, Carbonation Depth, Reinforcement Corrosion, Repairing

1. Introduction

To manufacture quality concrete structures, today's engineers must have a thorough understanding of the material itself, in regard to how it ages and how this aging affects the durability of the structure. This knowledge will enable the engineer to evaluate the present and future condition of the structure, and perform any necessary repairs to maintain a desired level of performance [1-2].

Concrete has a small tensile strength, making it easily cracked under impact or constant load. It also has material porosity, which is determined by the water-cement (w/c) ratio. The material porosity and cracks allow adverse action to affect the steel reinforcement, posing a serious problem for structure durability. For this reason, durability and strength are the most important aspects of concrete. Information gained is the key to successfully constructing concrete structures, and it happens to be a fact [3-4].

The concrete is an implant material, broadly used in the world of construction. Its fabrication types, such as cast-in-place concrete, precast, and prestressed concrete, as well as its deteriorating causes like steel corrosion and cracks, are unique factors not shared by other construction materials. Since the first existence of concrete, it has always been a curiosity object for researchers worldwide. Some of them work to invent new concrete inventions or supporting materials, while others work to inspect the actual condition of concrete and how long it can survive as a supporting structure [5-7].

One of the most common problems encountered with reinforced concrete is the corrosion of the steel

reinforcement. This corrosion is caused by the ingress of carbon dioxide from the atmosphere, which in turn reduces the alkalinity of the concrete pore solution to a point where the passive film on the steel is destabilized. Once this occurs, the corrosion process becomes electrochemical and will continue until the steel has lost its strength and the structure has lost its integrity. Carbonation of the concrete can be an early indicator of steel corrosion, as carbonation will in most cases precede any significant corrosion. This carbonation is the process, by which atmospheric carbon dioxide reverses the reaction which originally converted calcium hydroxide to calcium carbonate, and has the effect of reducing concrete pH [8].

Knowledge of the rate and distribution of carbonation over different concrete structures is essential in determining which structures are more susceptible to corrosion, and thus can aid in prioritizing maintenance and repair work [9]. This information is also crucial in identifying any changes in carbonation rate after the application of repairs, where an increase in carbonation may indicate a failure in the repair process. Carbonation can be measured using phenolphthalein indicator solution, which changes from pink to colorless at a pH of around 8.2 to 8.3. This color change can be detected on the surface of freshly broken concrete, and can also be used in the field with a hole being drilled to access concrete and obtain a sample. More recent innovations include the use of concrete surface pH sensors or pocket pH meters, which provide a more accurate assessment of carbonation. However, these methods are costly and may provide problematic results on aged, contaminated or very porous concrete [10-11]. The ability to accurately predict carbonation and corrosion rates could aid the development of a model to optimize the timing and selection of repairs, by allowing engineers to simulate the effects of various

repair strategies and compare the changes in deterioration rates. This would greatly help engineers to manage and extend the service life of existing concrete structures [12].

2. Overview of Carbonation of Concrete

Carbonation of concrete is a complex process which can have several negative effects on concrete structure. Carbonation is the reaction of the carbon dioxide in the air with calcium hydroxide and hydrates of the cement paste, leading to the production of calcium carbonate (Figure 1). This process is complex and dependent upon many factors. Chemically, the reaction is expressed as follows:



Generally, carbonation is slow at an early age as the high pH value of the concrete, normally above 10, provides a passivating environment which protects the steel reinforcement [13-15]. The carbonation front moves relatively slowly at from 0.5cm to 1.0cm per year but can be as high as 2.0cm per year. The rate is dependent upon the permeability of the concrete which tends to increase with age due to continued hydration and development of the concrete microstructure. Similarly, porosity and capillary characteristics govern the rate of ingress of carbon dioxide and influence the depth of carbonation [16].

Carbonation may be detrimental to concrete due to the reduction in alkalinity of the concrete and subsequent corrosion of steel reinforcement. Corrosion-induced cracking of the cover may then occur. Carbonation can also reduce the strength of the concrete and at high levels of carbonation, can cause a change in the structure of the hydrated cement paste as shown in Figure 1.

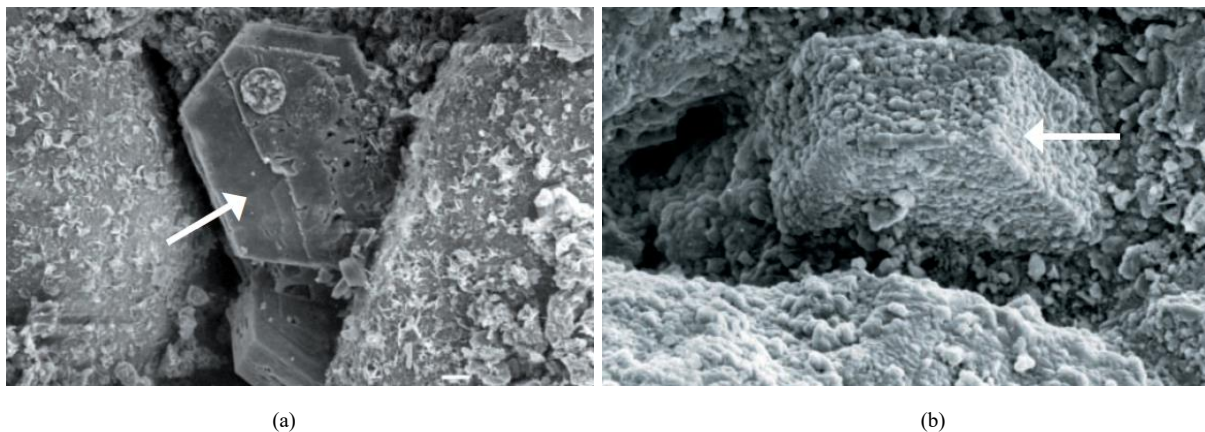


Figure 1. Portlandite crystal observed under a scanning electron microscope (SEM). (a): Non-carbonated portlandite crystal; (b): Portlandite crystal in the process of carbonation [17]

Calcium hydroxide reacts with carbonation to yield calcium and bicarbonate ions. This only moves the reaction to an equilibrium and a reversal of carbonation may occur if the concrete is exposed to a clean atmosphere. At a high level of carbonation, a white, chalky deposit may be seen on the concrete surface due to the formation of insoluble calcium carbonate. This can, in turn, stain the concrete and from an aesthetic point of view, is likely to require repair. High levels of carbonation would usually be considered anything in excess of 5% depth of cover and 10% carbonation of cement paste [18, 19].

The penetration of chloride ions contributes to the depassivation of the steel by modifying the composition of the passive layer. The chlorides contained in concrete can come either from:

- The concrete itself: via mixing water, an adjuvant or aggregates containing chlorides;
- From the external environment: sea spray, de-icing salts or chemicals which penetrate into the concrete by diffusion and/or by convection depending on the saturation rate of the material.

Initiation of corrosion by chlorides is only possible when the chloride concentration exceeds a critical concentration. In general, we consider that the initiation threshold is of the order of 0.40% of total chlorides relative to the mass of cement although this criterion is widely discussed and is the subject of numerous studies and publications. We must not forget that this value corresponds to the quantity of chloride ions that should not be exceeded at the time of manufacturing the concrete.

3. Measurement of Carbonation

3.1. Importance of Measuring and Repairing Carbonation

Carbonation is the reaction of CO_2 with Portland cement concrete. It is not a process which affects the concrete, but it will generally lower the pH of the concrete pore water to a value of between 8.5 and 9. This is because the carbonic

acid is formed by the reaction of CO_2 and the alkalis, calcium hydroxide, and the monosulfate hydrate phases. This will affect the passivity of the steel rebar in the concrete, meaning that the high alkaline state of the pore water in normal concrete will provide a protective oxide layer for the steel. When the pH drops below 10, the rate of corrosion dramatically increases. The effect of pH drops on the state of corrosion of reinforcements is given in Table 1.

Table 1. Effect of pH drops on the state of corrosion of reinforcements

pH of concrete	State of reinforcement corrosion
< 9.5	Commencement of steel corrosion
8.0	Passive film on the steel surface disappears
< 7.0	Catastrophic corrosion occurs

3.2. Phenolphthalein Spray Test

Measures of carbonation in the field are a very useful predictor for the likelihood of corrosion in the structure. The phenolphthalein test can be adapted to determine the carbonation front of the concrete. This requires a solution of 5% phenolphthalein in 80% methylated spirits. The appearance of the uncarbonated paste in the presence of phenolphthalein is bright pink, while the carbonated paste will stain no color. Carbonation depth is measured according to BS EN 14630 by spraying phenolphthalein, which changes color from red to yellow when the pH drops below 8.3, onto freshly broken concrete or by drilling cores into the concrete and then using a more precise litmus paper method. Figure 2 shows the processes involved in the phenolphthalein test.

High-resolution indicator papers or a pH electrode can be used to test the pH of the concrete pore water at various depths. Due to the differing reactivity of the various concrete ingredients, carbonation is not usually uniform across a structure [20]. Depth to steel indicators has not yet been proved reliable. The complexity of the carbonation process and the lack of reliable measures of predicting the remaining life of structures from the extent of carbonation show that carbonation and its mitigation are still not completely understood [21].

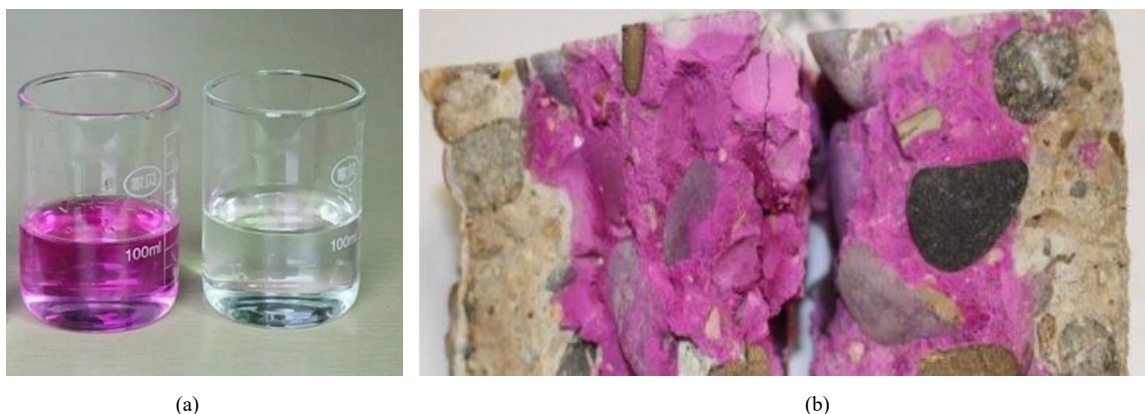


Figure 2. Phenolphthalein Test. (a): Phenolphthalein indicator; (b): Carbonated and non-carbonated concrete

The rate of carbonation slows with time as CO₂ penetrates deeper into the concrete and the pores become plugged with calcium carbonate. The following formula can be used to calculate the approximate depth of carbonation:

$$D = K_C \cdot (t)^{\frac{1}{2}} \quad (2)$$

Where, D is the carbonation depth (mm), K_C is the carbonation coefficient, a function of the quality of the concrete and its exposure [mm/(years)^{1/2}], t is the age of concrete (years).

Surprisingly, carbonation has little direct impact on the mechanical characteristics of concrete. In fact, carbon dioxide, when in high concentration in a humid atmosphere, penetrates the pores of the concrete and reacts with the carbon hydroxide present in the cement constituting the concrete. This reaction, which evolves from the surface towards the interior of the concrete element, induces a change in the chemical properties of the concrete. Concrete naturally has the ability to protect coated reinforcements against corrosion. On the other hand, when it is carbonated, concrete loses this capacity. The reinforcements therefore find themselves directly exposed and weakened against

corrosion. Thus, in the presence of humidity and oxygen, these reinforcements corrode.

According to Tuutti, the corrosion of reinforcements in concrete takes place in two periods:

- Initiation period: characterized by a passive state of the metallic reinforcement. During this period, the alkaline solution in the pores of the concrete produces rapid oxidation on the surface of the steel to form a stable protective layer called a passive film [22]. Consequently, the corrosion rate becomes low. The end of this first phase is marked by the depassivation of the steel and caused by the penetration of aggressive species into the concrete;
- Propagation period: Occurs following the modification of the composition of the pore solution in the vicinity of the reinforcement. Oxides and hydroxides produced by oxidation reactions on the surface of the steel begin to accumulate. The formation of these expansive oxidation products leads to swelling which will ultimately cause the concrete coating to crack. This behavior leads to an acceleration of corrosion by the creation of new preferential paths for aggressive agents (Figure 3).

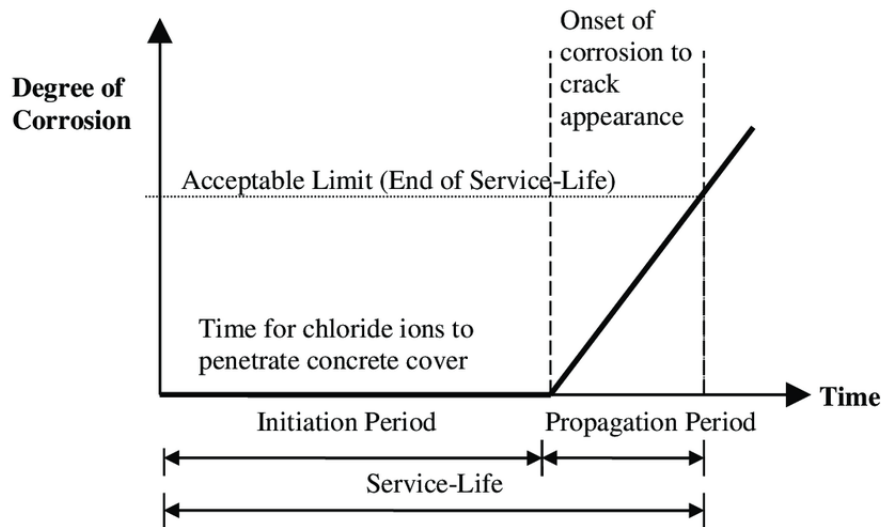


Figure 3. Tuutti diagram: periods of corrosion of reinforcements in concrete

The extent of carbonation will give an indication of the depth of carbonation front into the concrete. Depths up to 10mm will be classed as shallow carbonation, while more than 10mm depth will be classed as deep carbonation. Qualitative assessment of carbonation gives a guide to expected loss of alkalinity in the concrete, which is the level of carbonation at which depassivation of reinforcement will begin. Carbonation in good quality concrete will cause depassivation at a level of 12-20% pH. Depth of carbonation can also identify the specific areas and elements affected by carbonation and give a guide to the rate of carbonation for any predictive assessments that may be required. These are all valuable assessments which are not possible with a simple yes or no answer as to the presence of carbonation in concrete. Any further investigation and assessment will require a simple yet accurate way to determine the carbonation depth [23].

The benefit of measuring carbonation is to give an assessment tool to be used in the field or laboratory to determine the extent of carbonation in the concrete. When testing for carbonation with phenolphthalein indicator, we may not always have the time for full depth extraction to determine carbonation depth. Whether you are investigating a corrosion problem, assessing the durability or just keeping stock of products in the factory, a quick and accurate assessment of the extent of carbonation in concrete can give a useful insight into the problem. This assessment may only be to determine whether further more detailed investigation needs to be carried out with other tests [24].

3.3. Indicator Solution Method

The Indicator Solution Method is based on the reaction between the calcium hydroxide in the concrete, which is produced as a by-product of the hydration process, and CO_2 to produce calcium carbonate. The method involves firstly making a water extract from the surface of the concrete to be tested. This is achieved by vigorously rubbing a small area of the concrete with a soft brush to remove any loose materials, then carefully collecting the liquid film in a small petri dish. If the concrete is very porous, it may be necessary to use a small amount of distilled water to aid the collection process [25]. A small portion of the extract is then placed in another petri dish, and a drop of 0.1N hydrochloric acid is added to it. The acid is used to determine if there has been any carbonation of the concrete extract during previous testing and handling.

If effervescence is observed, this indicates that the sample has possibly been contaminated with CO_2 , and therefore it should be discarded, and a new extract taken from the concrete.

Once it has been established that the extract has not been pre-carbonated, it is then titrated with standardized 0.1N sodium hydroxide solution to which a pH indicator with a color change interval between pH 8.3 and 10.0 has been added. Due to the nature of the carbonation front in concrete, it is necessary to perform duplicate analyses on the water extract, one for the uncarbonated sample, and one for the sample after it has been artificially carbonated [26]. The carbonation of the extract can be achieved by placing another petri dish of the extract in a sealed container with a high concentration of CO_2 . This will reduce the pH of the extract when in contact with the CO_2 , and it can then be compared to the pH of the uncarbonated sample.

3.4. Concrete Core Extraction Method

Concrete core extraction method has been used for several years as a means of directly testing for the presence or absence of carbonation, and to give an indication of the extent of carbonation according to standard NF EN 12504-1. A number of techniques have been used to locate the position of reinforcement and thus avoid damaging it during drilling. The most common method is to use a cover meter, an instrument which can give an indication of the depth of concrete cover over reinforcement and a rough estimation of the diameter of steel present (Figure 4 (a)). Where this equipment has not been available, resort has been made to drilling a small exploratory hole to find the reinforcement and to careful use of power-driven tools under visual supervision. The accuracy of these methods in locating reinforcement can vary considerably.

Sampling is usually confined to suspect areas from which visual inspection, previous test results, or service records suggest that carbonation may be present. When drilling cores, it is essential that attention is given to the protection of the drilled hole and all exposed reinforcement during and after the drilling operation. This is necessary to prevent ingress of chloride ions which may cause corrosion of reinforcement and to prevent staining of the concrete surface from slurry or water exiting the drill hole. After the drilled core has been removed (Figure 4 (c)), it should be visually inspected to ensure it has come from the correct location and then marked in some way to show the exact location within the structures it was extracted from.

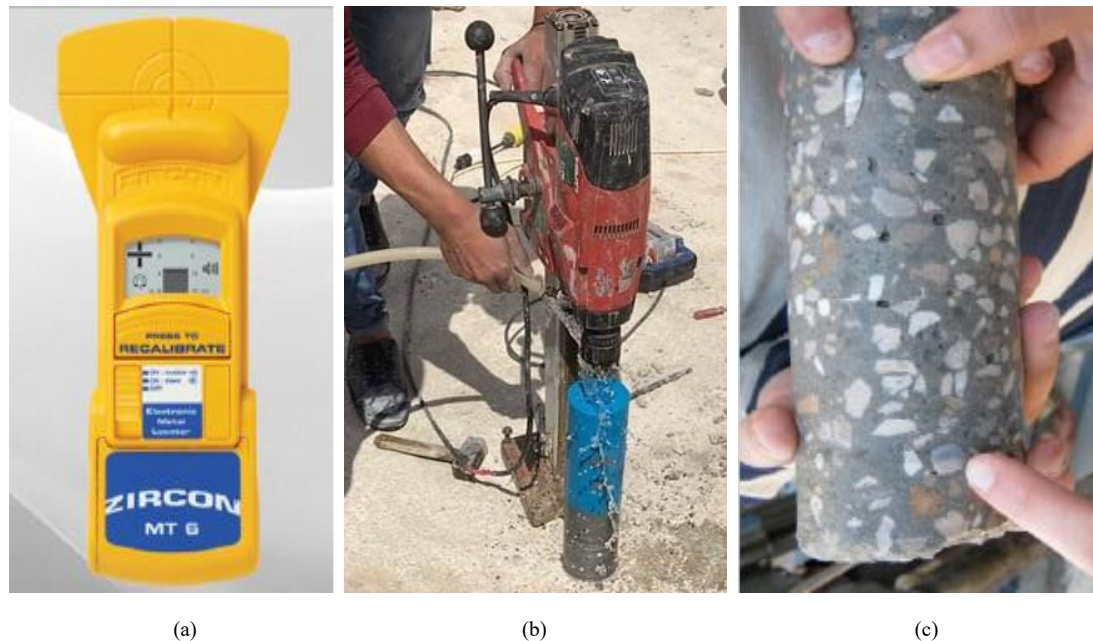


Figure 4. Concrete core extraction method. (a): cover meter; (b): core cutting device; (c): visual examination of core specimen

4. Influential Factors on the Corrosion of Reinforcements in Concrete

4.1. Effect of Composition of Concrete on Reinforcement Corrosion

The type of aggregate used and its porosity will dictate its capacity to absorb and store chlorides and will compromise its ability to protect the embedded steel. An increase in the size of the aggregates used will reduce the porosity of the concrete and increase its resistance to chloride ion penetration, therefore increasing the life of structures in aggressive environments. Recycled aggregates should be avoided as they have a higher porosity and water absorption rate, as well as a higher chloride ion content from the demolition of the structure. This is an example of where cost effectiveness of materials compromises the quality and durability of structures. High porosity lightweight aggregate concrete is the most susceptible due to its high absorptivity and high chloride ion content [27].

The presence of additives such as fly ash, silica fume or blast furnace slag in the formulation of concrete generally has a beneficial effect on the material [28]. These additives produce a very clear reduction in the permeability, diffusion coefficient and conductivity of the concrete.

4.2. Effect of Water Cement Ratio (W/C) on Reinforcement Corrosion

Water-to-cement (w/c) ratio is the most important factor affecting the durability and corrosion potential of reinforced concrete. It determines the ease of compaction and the potential for voids, which are vital to the ingress of

aggressive substances. The relationship between w/c and reinforcement corrosion is complex, since variation in w/c affects both the concrete properties and the corrosion environment. At low w/c, concrete has a reduced conductivity and chloride diffusion is slow. This decreases the corrosion risk, given that steel will not corrode without a minimum threshold of chloride concentration. Consequently, the relationship between w/c and reinforcement corrosion risk often seeks to assess its indirect effects via concrete conductivity and chloride threshold levels. This is useful in predicting the corrosion risk in a given exposure environment, but it may oversimplify matters and disregard the detrimental effects of localized corrosion events. Usually when w/c effects are examined in the context of a specific study, the chloride threshold level is used as an indicator of whether corrosion risk has increased or decreased. Some empirical studies have offered more general assessments, with Morf and Stucki considering a range of w/c to be critical, whilst Saric and Balog proposed a linear relationship to depict the increasing corrosion rate with increasing w/c [29].

4.3. Effect of Temperature on Reinforcement Corrosion

Setting time of concrete is influenced by its curing temperature and the gain or loss of heat of hydration. Especially in the case of pre-stressed concrete with steel tendons, if the steel is subject to force at a temperature less than that at which the concrete was poured, the steel will be subject to corrosion. An increase in temperature greatly increases the corrosion rate of the steel. For each 10 °C rise in temperature, the rate of reaction will approximately double. This occurs until the temperature of the steel reaches that of the concrete, where no further increase in

the corrosion rate will occur [30].

Anodic corrosion of steel in concrete increases with ease in the removal of iron ions to the concrete pore water, and an increase in temperature reduces passivation time before pitting corrosion occurs. High temperature can also reduce the passive state duration of steel. The minimum temperature for corrosion to occur can be considered from the temperatures of the setting time of concrete at around 10 °C. The temperature dependence of the corrosion rate of steel in concrete has been explained by the Arrhenius equation as follows:

$$k = k_0 \cdot e^{-\left(\frac{E}{RT}\right)} \quad (3)$$

where k is the kinetic reaction rate, k_0 is the rate constant, E is the activation energy, R is the universal gas constant and T is the absolute temperature.

However, in both types of anodic dissolution and depassivation, the corrosion rate will increase exponentially with temperature due to an increase in rate constants. The influence of temperature has been empirically established to have several effects on the corrosion of steel in concrete. These effects are some variations on the corrosion rate, the passive state of the steel, and the setting time of concrete. Considering the corrosion rate of steel in concrete in general, it is beneficial to determine any temperature limits [31].

4.4. Effect of Relative Humidity on Reinforcement Corrosion

The effect of the humidity level or degree of water saturation in the concrete is an important element because the corrosion rate of the steel strongly depends on it. This parameter has a direct influence on the conductivity and resistivity of concrete as well as on the diffusion of oxygen in the material. The corrosion of reinforcements in an unsaturated environment has been the subject of numerous studies [32-33] which have shown the existence of a degree of critical relative humidity close to 60%, below which no noticeable corrosion occurs.

The relative humidity most favorable to the appearance of corrosion varies between 70% and 80% [34]. The higher the humidity level, the greater the conductivity of the concrete becomes. However, under these conditions, the diffusion of oxygen towards the framework becomes more and more difficult.

4.5. Effects of Resistivity on Reinforcement Corrosion

The corrosion susceptibility of reinforcements is directly influenced by the resistivity of the concrete. Higher resistivity, lower corrosion activity and vice versa. Following facts would infer the above statement. Some authors have measured the corrosion rate of reinforcement embedded in concrete and immersed in 16 different solutions and found a unique linear relation between the

resistivity of concrete and corrosion rate of reinforcement. The connection between resistivity and corrosion activity is logical and inductive within an electrolyte (concrete is an alkaline electrolyte, $\text{pH} > 7$). The rate of anode dissolution and cathode formation can be realized by Tesla's law which states that the rate at which a metal goes into solution at the anode in an electrolyte is approximately proportional to the difference in potential between the metal and a standard electrode potential for that ion, which may be determined by the cell potential. Basically this would require setting up and testing apparatus which is impractical for determining corrosion rate in a structure. The corrosion cell can also be characterized by the flow of ions; anions towards the anode and cations towards the cathode. It is clearly seen that resistivity testing is the most feasible means of determining corrosion activity and service life of a structure. Table 2 presents the correlation between the measured resistivity of concrete and the probability of corrosion of reinforcements.

Table 2. Relationship between resistivity and corrosion rate of steel in concrete

Electrical resistivity (K Ω .cm)	Corrosion rate
< 5	Very High
5-10	High
10-20	Moderate
>20	Low

5. Repairing Carbonated Concrete

The repair of carbonated concrete is not only undertaken to halt the corrosion of the reinforcement but also to reinstate the durability and strength of the concrete. Surface treatments have been, in the past, the most common approach for repairing carbonated areas of concrete. Grinding techniques are effective in the removal of carbonated and contaminated concrete adjacent to the area being repaired. However, they have their limitations in the width and depth of contamination removal and can be costly. Wet grit blasting and high-pressure water washing are effective in the removal of contamination and require a lower degree of surface profile correction after the repair [35]. Repair materials can often be macadam or a slurry, both of which will need the use of a trowel to finish and will not add extra protection against future contamination. Wet methods can result in further carbonation of concrete due to water ingress and can often be limited to use in areas without water containment legislation [36].

Repairing carbonated concrete is a process involving the removal of the unsound material and replacement with new concrete. Various repair methods were reviewed in a recent RILEM report. The most prominent was the development of in situ pore-blocking methods primarily through injection of various resins and urethanes. These methods

aim to block the ingress of CO₂ without addressing the underlying problem of high alkalinity, which leads to carbonation [37]. Removal of the carbonated material and treating the underlying alkali silica reaction (ASR) or chloride-induced corrosion are still important aspects in repair that cannot be overlooked. However, the work in pore-blocking treatments has been a reaction to the shortcomings of current repair practices [38].

It is a little-known fact that properly carbonated concrete is actually quite durable in aggressive environments, as the high carbonation level provides a protective alkalinity at the reinforcement level. Rain, though it may initially damage the concrete, will actually strengthen the concrete in the long term, as the increased porosity due to damage will accelerate the carbonation process. However, if the concrete has been only partially carbonated, it will have both a higher pH at the reinforcement level and a higher moisture content due to lack of a significant increase in porosity, making it more susceptible to corrosion at this point than fully carbonated concrete. At any given time, it is estimated that over a billion square meters of concrete are in need of repair, due to steel reinforcement corrosion and spalling.

5.1. Injection Methods for Deeper Repairs

Approximately 3% of the grout volume is lost in the process of injecting it into concrete. This can be attributed to the leaking of the grout from the repair area, and the absorption of grout by the surrounding concrete. Patency, the condition of the concrete pores, is an important factor in determining the success of the repair. High patency will result in a large loss of grout and possibly voids in the repair area, while also affecting the bond strength between the old and new concrete. It is also possible that the grout will form a layer between the new and old concrete, leaving the repair area susceptible to water penetration and further corrosion of the steel [39].

An effective repair method involves removing the contaminated concrete. Doing so leaves a wider repair area and more exposed steel. A cement-based grout is more effective in this situation, as it will bond to the patch of new concrete, it is simple to make on site, and it can be easily mixed to a desired flowable consistency. The composition of the grout is important. A British study compared the effectiveness of various cement-based grouts and found that a high cement-to-water ratio increased compressive strength and impermeability, and reduced porosity, which is a key factor in corrosion inhibition. A significant increase in chloride resistivity was also measured.

Injection, using either epoxy or a cement-based grout, has been the main method of repair for damaged structural elements. This is the only method that returns the concrete to its original pre-damaged state, in terms of strength and durability. Epoxy injection has been successfully used in a variety of applications such as sealing narrow cracks. However, the bond strength between the concrete and the

epoxy is often stronger than the tensile strength of the concrete, resulting in a new crack forming near the original crack. Furthermore, it is very difficult to control the depth of the injection when the concrete has cracked due to corrosion of embedded steel [40].

5.2. Protective Coatings for Long-term Durability

One class of coatings, based on the alkoxy silane molecule, does offer some promise. When applied to dry concrete, it penetrates and reacts with the calcium hydroxide to form a silica gel within the pore system. This gel can fill the gel pores, blocking ingress of aggressive species such as carbon dioxide. Since the formula of the gel is similar to that of the hydrated cement paste, the coating is relatively stable and does not debond. However, it can be eroded if exposed to running or stagnant water. A similar reaction occurs when the silane is applied to concrete and allowed to cure before water contact. Unfortunately, this application will not produce significant carbonation resistance since the reaction requires moisture.

An alternative method to mitigating the effects of carbonation involves protecting the concrete from exposure to carbon dioxide by applying a protective coating to it. Several coatings are available, but traditional barrier type coatings based on epoxy, polyurethane, acrylic, or vinyl polymers are not entirely satisfactory since they do not bond well to the alkaline surface of the concrete and eventually delaminate. Also, if they are permeable to moisture, carbon dioxide may be transported to the alkaline environment at the concrete-coating interface resulting in carbonation and corrosion of the concrete.

5.3. Preventive Measures to Avoid Carbonation

It is preferable to use preventative measures to try to avoid carbonation where possible. Carbonation is a natural process, which can be controlled but never totally halted. Some of the preventative measures are the same as those used for chloride attack and involve reducing the ingress of carbon dioxide to below the level at which corrosion will commence, i.e. 0.02%. This is mainly achieved by increasing the cover of the steel. However, it is necessary to have a greater depth of cover for carbonation than for chloride to allow for any localized defect in the cover. A depth of at least 25mm is recommended, and the use of low permeability concrete cover will be more effective at a reduced depth. Carbon dioxide also enters concrete by a process of absorption, therefore a greater level of carbon dioxide can enter the concrete at later stages of the structure's life where the relative humidity of the environment increases. Ingress of carbon dioxide by absorption can be reduced by use of low permeability finishing surface or a painted or sprayed-on sealer coat. This can be an effective method if the sealer coat remains intact and bonded to the concrete, but it may require re-application during the service life of the structure.

Measures to keep relative humidity low within the concrete are also effective. This can require consideration of mix design as the use of high levels of supplementary cementitious material can increase the time taken for carbonation around the reinforcement. Prior to dehumidifiers are also effective in stopping carbonation in storage structures which are no longer in use.

6. Conclusions

The present paper has presented the carbonation process of concrete and the methods available for the determination of the carbonation depth, assessing the quality of the concrete, and repairing the damaged concrete. The following results have been deduced:

1. Carbonation is the principal cause of reinforcement corrosion in many concrete structures. This is because the process lowers the pH of the steel to below 10.5, at which the passive layer on the steel begins to break down.
2. Water cement ratio (W/C) is the most important factor affecting the durability and corrosion potential of reinforced concrete.
3. The most advanced corrosion happens at relative humidity above 65%; less than this, a thin layer of iron carbonate will form which is not too detrimental.
4. The corrosion rate drops off significantly at low relative humidities, as the steel becomes starved of oxygen, however it never drops to zero.
5. The ability to measure the depth of carbonation and thus detect its presence has very important repercussions on the repair of a carbonated concrete structure. This, coupled with the fact that a large number of tests in Europe have shown that carbonation rates are still increasing some 50 years post-construction, suggests that the repair of carbonation-induced defects will continue to be a major area of research in the field of concrete durability for some time.

The phenolphthalein test is able to measure with any degree of certainty that concrete has not carbonated and is therefore at risk for any quality, durability, and corrosion issues associated with carbonation.

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