

EFFECT OF WATER-CEMENT RATIO, CEMENT DOSAGE, TYPE OF CEMENT AND CURING PROCESS ON THE DEPTH OF CARBONATION OF CONCRETE

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ABSTRACT

In recent years, the durability of concrete has been the subject of a few research projects carried out by several scientific and technical centres. As a major cause of concrete degradation around the world, reinforcing steel corrosion requires our full attention. This article analyses one of the phenomena at the origin of these disorders, namely the carbonation of concrete, and proposes some provisions to guard against it. The article is divided into two parts; the first describes the causes and consequences of the chemical process of carbonation as well as the means to protect it. The second deals with the influence factors on carbonation such as the minimum cement dosage, the type of cement, the water-cement ratio (W/C) and the reinforcement coating. Indeed, prismatic specimens (15 x 15 x 60 cm³) and cubic specimens (15 x 15 x 15 cm³) were made for different mixtures and with a W/C ratio of 0.50, 0.55 and 0.60. The prismatic specimens were subjected to a carbonation test, while the cubic specimens were used to determine the compressive strength, the corresponding density and the immersion water absorption.

KEYWORDS

Durability, Carbonation depth, Concrete, Reinforcement corrosion, Cement, Dosage

INTRODUCTION

Concrete exposed to the air is subjected to an aging process that results from the reaction of carbon dioxide (CO₂) in the air with the alkaline constituents of the material. This reaction is called carbonation.

The carbonation of concrete is an inseparable phenomenon of this building material. During the lifetime of the structure, the carbon dioxide in the atmosphere enters the concrete from the surface of the material. A young concrete has a high pH which is around 12 to 13. This alkalinity leads to the formation, at the periphery of the reinforcements, of an almost impenetrable layer of iron hydroxides insulating the steel and stopping the process of corrosion. We talk about passivation of steel. During the life of the structure, the confrontation of concrete under the action of chemical environments such as sulfate reactions, alkaline reaction and carbonation can cause their degradation [1-3]. The concrete traps carbon dioxide at the level of 10 to 15% of the CO₂ emitted during the decarbonation of the limestone necessary for the manufacture of the cement. During the twentieth century, engineers learned to master certain problematic consequences of the carbonation phenomenon. At the end of the life of the structure, this time carbonation can be

exploited to fix CO_2 in the hardened cement paste of a demolition concrete. Recent results show that it is then possible to adjust up to 50 to 60% of additional CO_2 . Moreover, this carbonation is particularly favourable for improving the quality of the recycled granulate from the demolition concrete, thus facilitating its reuse.

Unlike the harmful consequences of carbonation on the durability of concrete structures, carbonation is rather a beneficial phenomenon from the point of view of the concrete material itself. It is indeed to recognize that the carbonation of cement matrices based on CEM I type cement is achieved with a mass gain corresponding to the fixation of CO_2 in the hydrates. The fact that the molar volume of the calcium carbonate formed is greater than that of the hydrates leads to clogging of the microstructure which makes the concrete less permeable to aggressive agents (in this case CO_2 and O_2 gases, but also sulphate ions, chlorides, and more generally, aggressive waters such as seawater, selenite or magnesian waters, ...).

It has even been shown that carbonation makes it possible to increase the mechanical resistance of concrete and to make the material more chemically stable vis-à-vis swelling reactions (internal or external sulfatic reaction, alkali-aggregate reaction). On the other hand, the modulus of rigidity or modulus of elasticity is increased, which is not always perceived as an advantage because this can lead to embrittlement of thin parts and to a heterogeneity of resistance and shrinkage in the case of coatings of partially carbonated facades where surface cracks can be observed which stop at the level of the non-carbonate internal zone.

A lot of research has been done to find out the influence of the W/C ratio on the carbonation rate. Papadakis et al. [4] show that the depth of carbonation is doubled when the W/C ratio goes from 0.5 to 0.8. The study by Loo et al. [5] focused on the influence of the W/C ratio and the cement content. Their results have led to consider that the most important parameter is the W/C ratio and that the cement content remains by comparison insignificant.

Taylor et al. [6] observed a decrease in carbonate thicknesses when the cement content increases. Two concomitant explanations for the decrease in the rate of carbonation are noted in the literature [6,7]:

- On the one hand, the quantity of lime to carbonate per unit of volume increases with the dosage of cement. The carbonation time is then longer, the carbonation speed decreases. Note that the amplitude and depth of carbonation also decreases.
- On the other hand, the compactness of the material tends to increase with the dosage of cement. The decrease in the amount of mixing water, induced by a higher dosage of cement, reduces the porosity of the cement, thus slowing the penetration of CO_2 into the porous network. Consequently, the carbonation rate decreases.

Muller and Sickert [8] compared the carbonation resistance of concretes made from ordinary Portland cement or cement based on blast furnace slag. They have shown that cement mixes based on blast furnace slag carbonate much faster than Portland cement mixes for an identical W/C ratio. Their study has also shown that only cement concretes based on blast furnace slag are carbonated.

Kobayashi and Uno [9] studied the carbonation rate of concretes made with cements with different alkaline contents. Their results from accelerated carbonation and natural carbonation tests have shown that an increase in the alkali content leads to greater carbonation of the concrete. These authors also studied the influence of the alkali content at different W/C ratios; they showed that an increase of 0.6% in alkali is equivalent, from the point of view of carbonation, to an increase in W/C ratio of 0.10.

Loo et al. [5] have shown that the carbonation rate decreases with the duration of an underwater cure regardless of the compressive strength of the concrete at 28 days. They noted that after 14 days of treatment, the improvement is less. They also carried the carbonation coefficient as a function of the inverse of the square root of the compressive strength. They found that the points line up on the same straight line whatever the duration of the cure, which means

that the improvement in resistance due to the cure is the preponderant factor responsible for the reduction in the carbonation rate.

Fattuhi [10] studied the improvement brought by a cure of concrete under water. The results of the accelerated carbonation tests have shown that concretes subjected to a cure in water of 1, 3, 5, 7 and 28 days respectively have a carbonation rate of 66, 63, 42, 39 and 17% compared to a cure performed in the air.

Gruyaert et al. [11] have shown that a curing period longer than 1 month significantly improves the durability properties of slag cements. The effect of the cure is more appreciable for a slag cement because of its slower hydration kinetics [12,13]. However, for treatment duration of more than 3 months, the resistance to carbonation is no longer significantly modified. Furthermore, it seems that increasing the curing period does not have the same effect in the case of Portland cement or in the case of a composite cement [14]. The results of Lo and Lee [15] also tend towards this result. According to several authors [14,16], the effect of the cure on carbonation is minimal compared to the effect of the nature of the cement.

The carbonation of concrete is also correlated with other parameters such as mineral addition. Skenderovic [17] has shown that replacing part of the cement (10%) with silica fumes increases the rate of natural carbonation of the concrete although the porosity is considerably reduced. He explained this phenomenon by the lower quality of portlandite in concretes with silica fumes. In the study by Richardson et al. [18], the authors have shown that the addition of scilice fumes limits the depth of carbonation of the concrete. These contradictory results require further investigation to assess these additions under similar conditions of W/C ratio and curing of concrete samples.

For the addition of furnace slag, Skenderovic [17] and Malami et al. [19] have not obtained any significant change in the carbonation rate for cement replacements up to 30% and 15% respectively. They observed a significant increase in carbonation only for the replacement of 50% of the cement by slag.

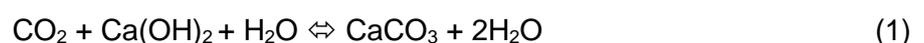
Papadakis et al. [4] studied the influence of fly ash on the depth of carbonation of concrete. The results of their analysis have been very marked when we exceed 15%. The replacement of aggregates with fly ash has an opposite effect but with a lesser tendency.

The main objective of this experimental study is to describe the causes and consequences of the chemical process of carbonation as well as the means to protect it. The influence of certain parameters on carbonation such as the minimum cement dosage, the type of cement, the water-cement ratio (W/C) and the reinforcement coating has also been studied.

CARBONATION AND CORROSION

Carbonation process

Carbon dioxide is diluted in the water contained in the porous structure of the concrete. This reaction allows the calcium hydroxide to dilute in turn in the interstitial water, to react with the CO₂ and to precipitate in the form of calcium carbonate, which lowers the pH of it to a value close to 9 [20-22]. Carbonation of hydrated calcium silicates (C-S-H) is also possible. The reaction is represented chemically as follows:



The carbonation of C-S-H, which contributes significantly to the fixation of CO₂ in the cement matrix, is responsible for important changes in the microstructure (Figure 1).

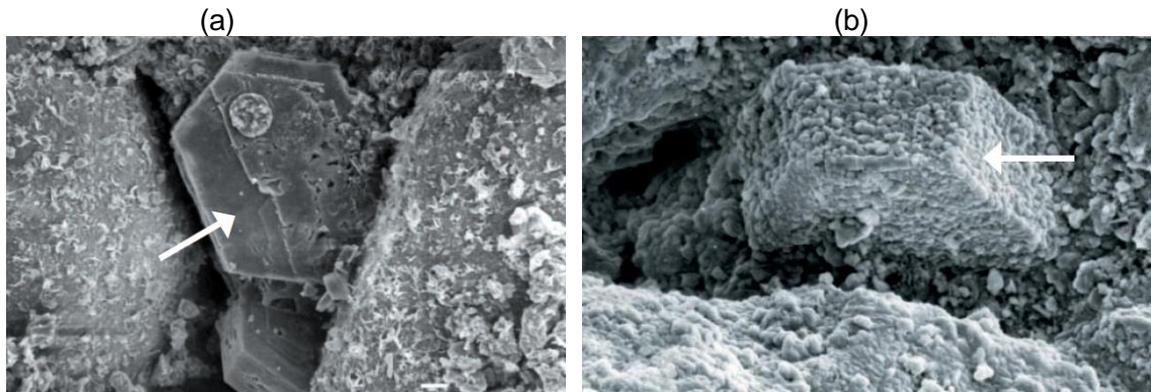


Fig. 1- Portlandite crystal observed under a scanning electron microscope (SEM). (a): Non-carbonated portlandite crystal; (b): Portlandite crystal in the process of carbonation.

Generally, corrosion of reinforcement begins with the drop in pH. At this stage, we notice a loss of passivity of the concrete against corrosion of the reinforcements. Table 1 gives the effect of pH drop on the state of corrosion of reinforcements

Tab. 1 - Effect of pH drop on the state of corrosion of reinforcements [23]

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

For most concretes, the precipitation of calcium carbonate (CaCO₃) results in an improvement in the compactness of the structure and a slight increase in compressive strength. In reinforced concrete, however, this reaction may lead to degradation due to corrosion of reinforcement. Over time, the carbonation front, which is the demarcation between the carbonate zone of the concrete and the intact zone, progresses more and more deeply in the structure (Figure 2).

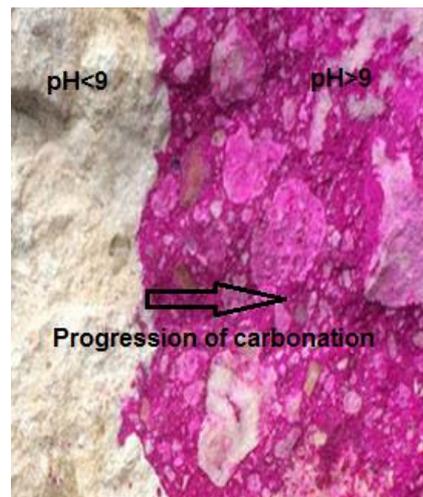


Fig. 2 - Progression of carbonation in concrete

However, the rate of carbonation decreases with time, since CO₂ must penetrate ever further into the concrete and the pores are clogged with calcium carbonate. The approximate depth of carbonation can be calculated using the following formula:

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

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

The carbonation coefficient K_C gives an indication of the concrete's resistance to carbonation; it depends on the composition of the latter, the cure achieved and the exposure of the structure. In a concrete exposed to a specific medium, the higher the coefficient, the faster carbonation will be and therefore the lower the resistance to the phenomenon.

As soon as the carbonation front reaches the reinforcement, the pH decreases in the area of the concrete located on the periphery of the steel, the passivation layer is destabilized, dissolves and its protective action disappears. If the structure also contains water and oxygen, the reinforcements will begin to rust. The corrosion products formed will occupy a volume several times greater than that of steel, which will lead to cracking and crumbling of the concrete.

In general, it is found that the corrosion of the reinforcements induced by carbonation affects the elements more or less uniformly over long distances (generalized corrosion). It is also reported that the resistivity decreases and corrosion rate increases with an increase in the chloride content [24]. In fact, the modification of the chloride content causes a slight variation in the pH value. Table 2 describes the level of corrosion of reinforcement as a function of the chloride content in the concrete.

Tab. 2 – Level of corrosion in concrete containing chlorides [25]

Chloride content	Condition of concrete adjacent to reinforcement	Level of corrosion
Less than 0.4%	Carbonated	High
	Uncarbonated, made with cement containing less than 8% C_3A	Moderate
	Uncarbonated, made with cement containing 8% or more C_3A	Low
0.4% - 1.0%	As above	High
	As above	High
	As above	Moderate
More than 1.0%	All cases	High

Measurement of concrete carbonation depth

The phenolphthalein method was used to measure the depth of carbonation according to BS EN 14630 [26]. Phenolphthalein is a coloured indicator used to estimate the pH in weak acid or strong base assays. It changes colour depending on the pH value of the solution. When the concrete is not carbonated, the phenolphthalein becomes red and it remains colourless in the case of carbonated concrete.

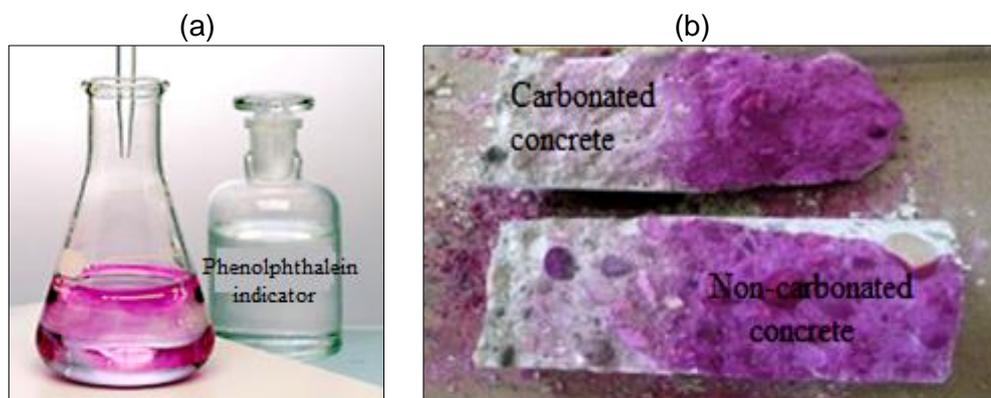


Fig. 3 - Phenolphthalein Test. (a): Phenolphthalein indicator; (b): Carbonated and non-carbonated concrete

The steps of the phenolphthalein test are as follows: (Figure 3):

- Break a relatively large surface or a concrete core in the lengthwise;
- Apply the phenolphthalein indicator solution to the surface to be tested. It is advisable to apply a light mist of water on the broken surface in the case of very dry concrete;
- Measure with a graduated ruler the distance between the edge of the red-purple coloured area and the exterior surface of the concrete and deduce the average depth of carbonation.

According to some authors [27-29], environmental conditions and exposure conditions influence the phenomenon of carbonation of concrete.

This procedure requires fairly large samples. To limit the damage due to sampling, another measurement method is used; this consists of drilling small holes 6 to 8 mm in diameter into the concrete and collecting the drilling powder on a sheet impregnated with phenolphthalein. In the case of a concrete slab, the powder can be sprinkled regularly with phenolphthalein. As soon as the drilling reaches the healthy concrete, the powder changes colour. The depth of the drilling then corresponds approximately to the depth of carbonation. The measurement should be made at least three times in each area examined to reduce the influence of local phenomena such as the presence of aggregates. It must also be taken into account that the depth of carbonation can be higher in cracks and angles.

Parameters influence carbonation kinetics

There are many models of carbonation that translate, more or less directly, the physicochemical resistance of concrete against the penetration of the carbonation front.

The parameters used relate to:

- The porosity of the concrete which conditions the "physical" resistance of the material to the diffusion of CO_2 ;
- The content of carbonatable hydrates: the higher it is, the more the concrete is able to "chemically" slow down the penetration of the carbonation front;
- The microstructure of the material (pore size) on which depends the hydrous state of the material which will condition the kinetics of penetration of the phenomenon. It is then essentially the liquid water permeability of the material that will be an indicator of relevant durability.

These models generally result in a slow evolution in the square root of the time of the carbonation depth. To fix ideas, with ordinary concrete preserved in an environment whose relative humidity is between 50 and 70%, the carbonation depth is 5 mm after one year, 10 mm after 4 years and 25 mm after 25 years.

The mechanism of concrete carbonation is affected by several internal and external factors. The Internal factors are cement type and content [27], curing conditions and curing time [30] and water cement ratio. The external factors are the relative humidity [31-33], sheltering, rain, CO_2 concentration and temperature [33,34].

Carbonation can also be the cause of disorders in the facade coatings generally corresponding to high-fat mortars ($\text{Ca}(\text{OH})_2$) partially carbonated.

The acidification of the medium that results from the attack of CO_2 can be at the origin of the development of microorganisms (lichens, mosses, algae, etc.) that do not grow in a strongly basic medium. These microorganisms are at the origin of unsightly stains. It is possible to temporarily remove these traces by washing the wall with diluted bleach or using a suitable fungicide product.

METHODS AND MATERIAL

Principle

The fundamental element that controls the carbonation of concrete is the diffusion of CO_2 through the hardened cement paste. This is why the requirements impose limit values for the

water-cement ratio (maximum) and the cement (minimum) dosage. Exposure of concrete (moisture content) has an influence on the carbonation rate.

The purpose of this work is to determine the influence of various parameters on the concrete's resistance to carbonation. The parameters studied were:

- The type of cement;
- The cure of concrete;
- The water-cement ratio (W/C);
- The cement dosage.

In the absence of a standard test procedure, a method has been developed to characterize the concrete's resistance to carbonation and to examine the influence of the above parameters. This test method is deliberately simple in nature so that it can be used both for testing site samples and for testing as part of a certification.

Test method

The concretes used in the research were composed of calcareous aggregates, the dimensions of which were distributed in accordance with standard NF EN 480-1 [35]. Different types of cement were used (CEMI 32.5N, CEMI 42.5N and CEMII A-L 32.5N) in conformity with Tunisian Standard NT 47.01 and European standard EN 197-1:2000 produced by the Cement Company of BIZERTE. Table 3 shows the chemical composition and compressive strength at 28 days of cement.

Tab.3 - Chemical composition and properties of cement

Chemical composition	Type of cement					
	CEMI 32.5N (%)		CEMI 42.5N (%)		CEMIIA-L 32.5N (%)	
Insoluble Residue (IR)	≤ 5		≤ 5		-	
Sulphur Trioxide (SO ₃)	≤ 3.5		≤ 3.5		≤ 3.5	
Magnesium Oxide (MgO)	≤ 5		≤ 5		≤ 5	
Chloride (Cl)	≤ 0.1		≤ 0.1		≤ 0.1	
Soundness (mm)	≤ 10		≤ 10		≤ 10	
Initial Setting Time (mn)	≥ 60		≥ 60		≥ 60	
Compressive strength at 28 days (MPa)	min	Max	min	Max	min	Max
	32.5	52.5	42.5	62.5	32.5	52.5

The mixtures were prepared with a W/C ratio of 0.50 and a cement dosage of 300 kg/m³. For cements CEM I 42.5 N and CEM II A-L 32.5 N, mixtures were also formulated with a W/C ratio of 0.55 and 0.60 (cement content 300 kg/m³) and cement dosages of 280 kg/m³ and 350 kg/m³ (W/C ratio of 0.50).

Prismatic specimens (15 x 15 x 60 cm³) and cubic specimens (15 x 15 x 15 cm³) were made for each mixture. The prismatic specimens were subjected to a carbonation test, while the cubic specimens were used to determine the compressive strength (at 28 days), the corresponding density and the immersion water absorption.

After a hardening of 24 hours, the samples were demolded and underwent two different treatments:

- An ideal cure: preservation for 56 days in an environment with (20 ± 2°C) and more than 90% relative humidity (RH);
- An unsatisfactory cure: preservation for 56 days in an environment at (20 ± 2°C) and (60 ± 2%) relative humidity (RH).

The long cure time (56 days) is intended to allow sufficient primary and secondary hydration. After this time, the specimens are dried for 14 days, and then stored at a temperature of 20 ± 2 ° C and a relative humidity of 60 ± 2% until constant mass.

The prismatic specimens were stored for 56 days in the carbonation chamber, within which the CO₂ content is regulated at 1%, the temperature at (20 ± 2°C) and the relative humidity at (55 ± 5%). A number of prismatic specimens were split after 3, 7, 14, 28, 35, 42 and 56 days to measure the average carbonation depth.

The different samples were subjected to several tests: resistance in compression, determination of the corresponding density and the absorption of water by immersion. Subsequently, correlations between these characteristics were established.

Measurements of porosity accessible to water on the concrete samples were carried out. This method is now the subject of an AFPC-AFREM operating mode which therefore ensures a homogeneous practice of this test and which allows a comparative treatment of the results, regardless of the laboratory where they were obtained. The results obtained provided an indicator of the quality of the mixture which is well correlated with the compressive strength: when the porosity decreases (due to a decrease in the W/C ratio), the strength increases.

RESULTS AND DISCUSSION

Measurement of concrete carbonation depth

The approximate depth of carbonation was calculated using the formula (2). The mean carbonation depth as a function of the square root of the exposure time (\sqrt{t} days) is given in Figure 4. When applying the phenolphthalein solution to the samples, it was noticed that the non-carbonated area takes on a dark pink colour, on the other hand the carbonated area remains colourless. Phenolphthalein therefore offers a simple reading of the depth of carbonation since the forehead is sharp and generates good colour contrasts. It was noted that concretes based on CEM II are more carbonated than concretes based on CEM I for all ages. We also observed on the samples that the carbonation front increases with the W/C ratio and with the time of exposure to CO₂.

It was also noted that after 35 days, the concretes based on CEM II were completely carbonated. This rapid carbonation is mainly due to the high value of the W/C ratio which influences the porosity and subsequently its permeability. On the other hand, the concretes based on CEM I were not entirely carbonated even after 56 days.

According to the carbonation models, the evolution of carbonate thickness follows a square root law of time. For our concretes, the depths measured over time do not strictly form a line segment. Indeed, several authors believe that the kinetics of accelerated carbonation does not obey a square root law of time. It associates the curvature of the kinetics curve of the carbonation front with the carbon dioxide depletion of the material by chemical carbonation reactions. Thus, it would not be a simple process of diffusion which follows kinetics in square root of time.

According to the results of Figure 4, it is noted that the kinetics ratio between the carbonation of concretes composed of CEM II and CEM I is associated with the lower content of portlandite in CEM II. As a result, a smaller amount of CO₂ is needed to consume the portlandite. These results are in agreement with the results of Papadakis et al. [4] who observed a faster rate of progression of the carbonation front in composite cement than in pure Portland cements.

The use of a concrete based on CEM I 42.5 and a W/C ratio = 0.50 made it possible to obtain a high performance concrete durable and resistant to carbonation. This result is mainly due to the good compactness of the concrete, which considerably reduces the penetration of CO₂ as well as the high reserve of Ca (OH)₂.

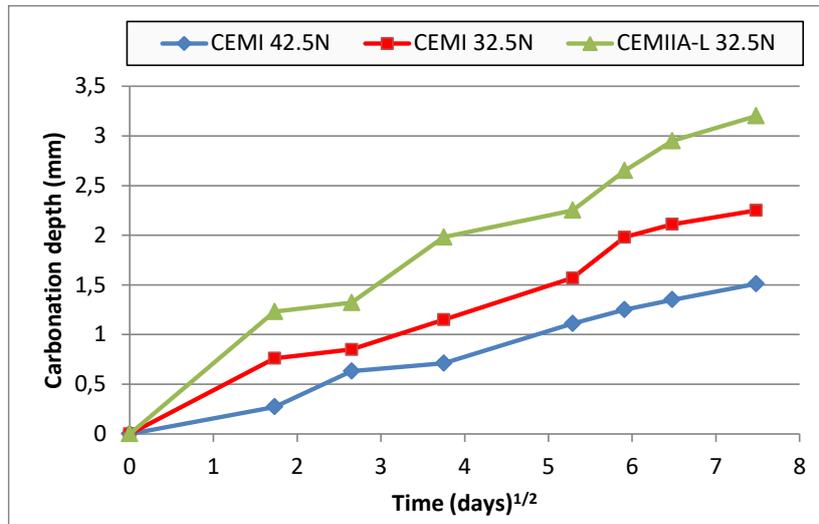


Fig. 4 - Determination of carbonation depth by linear regression coefficient

Effect of water-cement ratio (W/C)

The incidence of the W/C ratio was studied on concrete containing two types of cements (CEM I 32.5 N and CEM II/AL 32.5 N) dosed at a rate of 300 kg/m³. Figure 5 and 6 give the results obtained on three test pieces for each W/C ratio used. As expected, the resistance to carbonation increases as the W/C ratio decreases.

It is noted that the W/C ratio exerts a great influence on the porosity of the hydrated cement paste because it directly governs the initial spacing between the grains of cement suspended in the mixing water.

In fact, when the W/C ratio is low, the grains of cement become very close to each other and the carbonation decreases. The gaps between the cement grains are smaller and there is less chance of having a large void that cannot be completely filled by hydrates.

The reduction in the W/C ratio not only makes it possible to reduce the total volume of the capillary pores but it also makes it possible to reduce their diameter.

For a lower W/C ratio, the capillary porosity is in fact made up of a finer and more discontinuous network of pores.

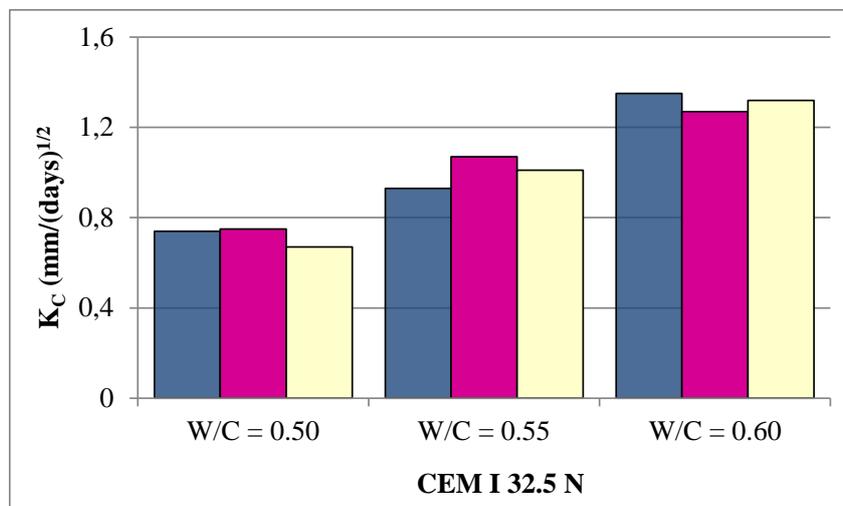


Fig. 5 - Effect of W/C ratio on K_C of cementitious concrete CEM I 32,5 N dosed at 300 kg/m³.

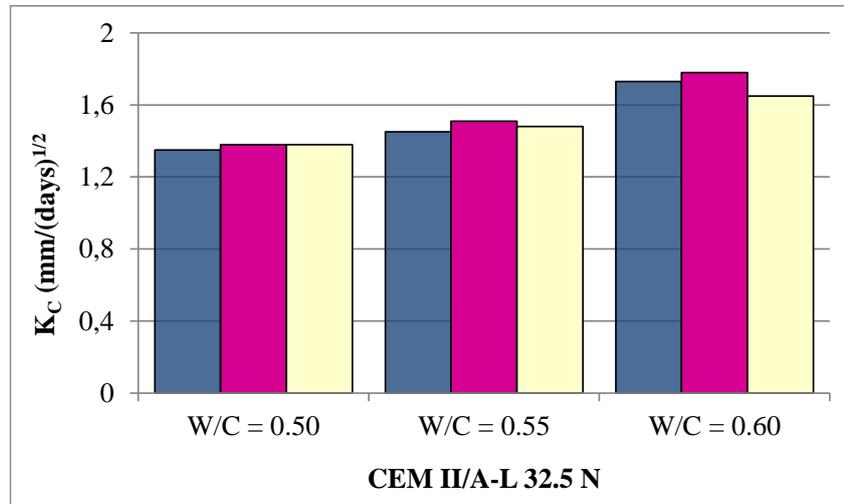


Fig. 6 - Effect of W/C ratio on K_C of cementitious concrete CEM II/A-L 32,5 N dosed at 300 kg/m³.

No macroscopic trace of carbonation was observed even after one month on the concrete containing cement CEM I, W/C = 0.50. Conversely, the concrete containing cement CEM II, W/C = 0.60 has a carbonation detectable from the first day of exposure to CO₂ and which turns out to be total from 20 days because of its high porosity.

It is also noted from the results of Figure 5 and 6 that the progression of the carbonation of the concrete containing the cement CEM I, W/C = 0.60 is similar to that of the concrete containing the cement CEM II, W/C = 0.50. This means that with regard to accelerated carbonation, increasing W/C from 0.50 to 0.63 is equivalent to moving from CEM I to CEM II.

Effect of cement dosage

The effect of cement dosage was also examined on cement-based concrete CEM I 42.5 N with a W/C ratio of 0.50. The results obtained on three specimens for each cement dosage are shown in the diagrams of Figure 7. We did not find any significant effect of the cement dosage on the carbonation resistance. However, it must be emphasized that the quantities of cement used during the study were relatively high and not very differentiated.

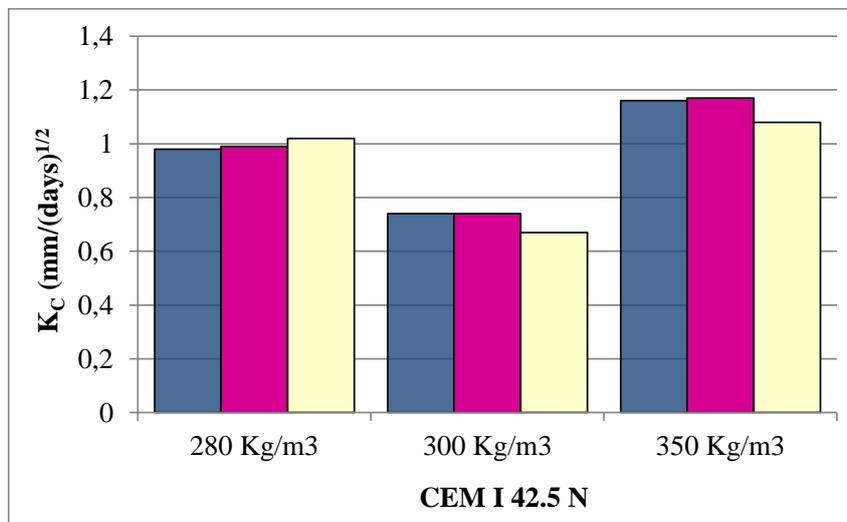


Fig. 7 - Effect of cement dosage on K_C of cementitious concrete CEM I 42,5 N.

Apart from the cement dosage, a major point influencing the degree of carbonation is the nature of the cement. Compound cements, which substitute part of Portland cement with mineral

additions (silica smoke, fly ash, blast furnace slag), carbonate differently depending on their compositions. In addition, a brief synthesis of the works relating to the effect of mineral additions on the rate of carbonation is proposed. Only the mineral additions used in the composition of the cements studied for this study are taken into account.

Effect of the type of cement

The carbonation coefficients K_C obtained with concretes formulated with different types of cement dosed at 300 kg/m^3 and having W/C ratio of 0.50 are presented in Table 4. The influence of the cement type has been demonstrated by comparing the carbonation coefficient of each cement with that of the CEM I 32.5 N (reference cement). Thus, it can be seen that with W/C ratio and identical dosages, the cement with additives (Calcareous Filler, Gypsum) have a higher carbonation coefficient than Portland cement. This unfavourable effect is accentuated, as the fineness of the cement decreases (passage from class 42.5 to 32.5 for the same type of cement).

Tab.4 - Carbonation coefficients K_C obtained with different cements and different curing processes

Cements	$K_C \text{ (mm}/\sqrt{\text{days}})$		Unsatisfactory cure/Ideal cure
	Ideal cure	Unsatisfactory cure	
CEM I 32.5N	2.22	2.79	1.26
CEM II/A-L 32.5R	1.15	2.29	1.99
CEM I 42.5N	0.72	1.57	2.18

Effect of curing process

The cure consists of taking protective measures to reduce the evaporation of water on the concrete surface or to preserve its moisture content. For in-situ concrete, several cure classes have been defined. These correspond to a cure time of 12 hours or the time required to reach a given resistance in compression (Table 5). The cure class must be specified in the performance requirements.

Tab.5 - Cure class [26]

Cure class	Percentage of the value specified for the compressive strength at 28 days
Class 1(*)	-
Class 2	35%
Class 3	50%
Class 4	70%

(*) Provided that the setting does not exceed 5 hours and the temperature on the surface of the concrete is equal to or greater than 5°C .

The results of research shown in Table 5 also show that the type of cure has a major influence on the resistance of concretes to carbonation. In fact, poor cure conditions lead to carbonation coefficients two times higher than those obtained on the series of specimens composed of the same cement but subjected to optimal conditioning.

Correlations with other common features

The carbonation coefficient is not a common evaluation criterion, nor is it a fast measuring device to control the quality of a concrete. This is why correlations with more conventional characteristics such as water absorption or compressive strength were established.

The absorption of water by immersion has been determined according to standard NBN B 15-215. The results of Figure 8 show that the absorption of water by immersion is between 4.4% and 6.3% for the concretes studied in the research.

We also note that the lowest carbonation coefficients were obtained with concretes with the lowest absorption values. However, the carbonation coefficients could not be directly correlated with the water absorption by immersion.

The type of cement, the W/C ratio, the cement dosage and the degree of hydration are also factors influencing the compressive strength of concrete; it was once common to consider that the resistance to carbonation was a function of the resistance in compression.

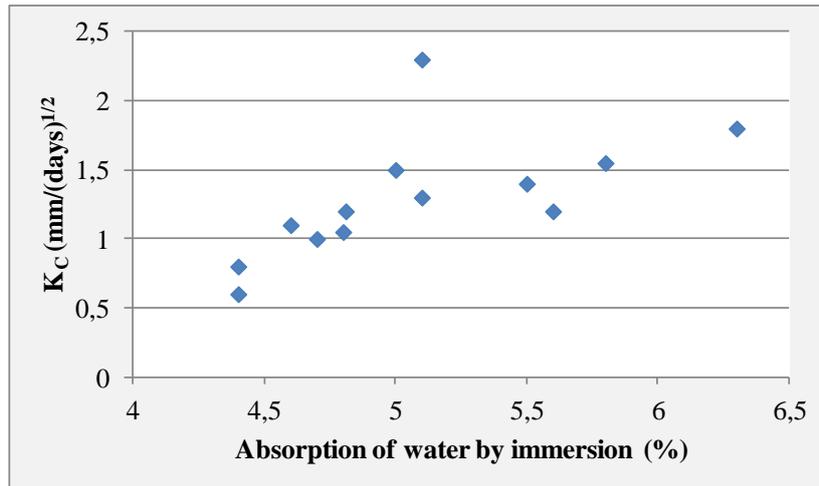


Fig. 8 - Correlation between K_C and absorption of water by immersion

However, as shown in Figure 9, there is no direct link between the carbonation coefficient and the compressive strength determined according to NBN EN 12390-3 at 28 days. At most it is noted that the carbonation coefficients are the highest in concretes of lower compressive strength and, conversely, the concretes that resist compression best also have the lowest carbonation coefficients.

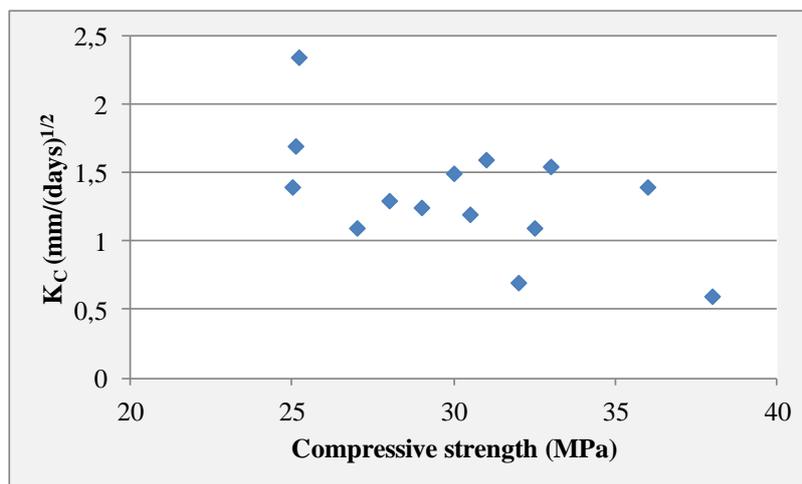


Fig. 9 - Correlation between K_C and compressive strength

CONCLUSION

The present paper has presented results of an experimental study conducted on prismatic and cubic specimens to analyse the phenomena of carbonation of concrete and proposes some provisions to guard against it. The following results have been deduced:

- The resistance to carbonation increases as the W/C ratio decreases for concrete containing two types of cements (CEM I 32.5 N and CEM II/A-L 32.5 N) dosed at 300 kg/m³.

- The cement dosage has no effect on the carbonation of the concrete specimens made with CEM I 42.5 N and W/C ratio of 0.50.
- The cements dosed at 300 kg/m³ and having W/C ratio of 0.50 with additives (Calcareous Filler, Gypsum) have a higher carbonation coefficient than Portland cement.
- The type of cure has a major influence on the resistance of concretes to carbonation. In fact, poor cure conditions lead to carbonation coefficients two times higher than those obtained on the series of specimens composed of the same cement but subjected to optimal conditioning.
- The carbonation coefficients could not be directly correlated with the water absorption by immersion.
- The carbonation coefficients do not have a direct link with compressive strength determined at 28 days.

REFERENCES

- [1] Monkman S., Mac Donald M., 2016. Carbon dioxide upcycling into industrially produced concrete blocks. *Construction and Building Materials*, 124:127-132.
- [2] Jedidi M., Abroug A., Moalla B., Benjeddou O., 2017. Non-destructive Testing for the Diagnosis and Repair of Reinforced Concrete Building. *International Journal of Architecture, Engineering and Construction*, 6(1): 20-28.
- [3] Mehta PK., 2001. Reducing the environmental impact of concrete: concrete can be durable and environmentally friendly. *Concrete International*, 61-66.
- [4] Papadakis VG., Fardis MN., Vayenas CG., 1992. Effect of composition, environmental factors and cement-lime mortar coating on concrete carbonation, *Materials and Structures*, 25: 293-304.
- [5] Loo YM., Chin MS., Tam CT., Ong KCG., 1994. A carbonation prediction model for accelerated carbonation testing of concrete, *Magazine of Concrete Research*, 46(168): 191-200.
- [6] Taylor R., Richardson IG., Brydson RDM., 2010. Composition and microstructure of 20-year old ordinary Portland cement-ground granulated blast-furnace slag blends containing 0 to 100% slag, *Cement and Concrete Research*, 40: 971-983.
- [7] Houst YF., Wittmann FH., 1989. Retrait de carbonatation, in: *Durabilities of Structures IABSE*, Lisbonne, pp. 255-260.
- [8] Muller A., Sickert G., 1995. Determination of the carbonation resistance of concrete on the basis of its capillarity and microstructure, *Betonwerk + Fertigteile-Technik*, N°11, pp. 70-88.
- [9] Kobayashi K., Uno Y., 1990. Influence of alkali on carbonation of concrete. Part I, Preliminary tests with mortar specimens, *Cement and Concrete Research*, vol. 19, N°5, pp. 821-826, 1990. Part II, Influence of alkali in cement on rate of carbonation of concrete, *Cement and Concrete Research*, 20(4): 619-622.
- [10] Fattuhi NI., 1988. Concrete carbonation as influenced by curing regime, *Cement and Concrete Research*, 18(3): 426-430.
- [11] Gruyaert E., Van den Heede P., De Belie N., 2012. Carbonation of slag concrete: Effect of the cement replacement level and curing on the carbonation coefficient - Effect of carbonation on the pore structure, *Cement and Concrete Composites*.
- [12] Gowripalan N., Cabrera JG., Cursens AR., Wainwright PJ., 1990. Effect of curing on durability, *Concrete International Design and Construction*, 12(2) 47-54.
- [13] Haque MN., 1990. Some concretes need 7 days initial curing. *Concrete International Design and Construction* 1990, 12(2): 42-46, *Concrete International: Design and Construction*, 12: 42-46.
- [14] Balayssac JP., Detriche CH., Grandet J., 1995. Effects of curing upon carbonation of concrete, *Construction and Building Materials*, 9: 91-95.
- [15] Lo Y., Lee HM., 2002. Curing effects on carbonation of concrete using a phenolphthalein indicator and Fourier-transform infrared spectroscopy, *Building and Environment*, 37: 507-514.
- [16] L.J. Parrott, Some effects of cement and curing upon carbonation and reinforcement corrosion in concrete, *Materials and Structures*. 29, pp. 164-173, 1996.
- [17] Skenderovic B., 1992. Effects of some additives on dynamics of carbonation, 9th International Congress of Chemistry and Cement New Delhi, vol. V, pp. 377-380.
- [18] Richardson IG., Groves GW., Brough AR., Dobson CM., 1993. The carbonation of OPC and OPC/silica fume hardened cement pastes in air under conditions of fixed humidity, *Advances in Cement Research*, 5(18): 81-86.

- [19] Malami C., Kaloidas V., Batis G., Kouloumbi N., 1994. Carbonation and porosity of mortar specimens with pozzolanic and hydraulic cement admixtures, *Cement and Concrete Research*, 24(8): 1444-1454.
- [20] Saetta AV., Vitaliani RV., 2005. Experimental investigation and numerical modeling of carbonation process in reinforced concrete structures: Part II. Practical applications. *Cement and Concrete Research*, 35:958-967.
- [21] Jedidi M., Benjeddou O., 2018. Chemical Causes of Concrete Degradation. *MOJ Civil Engineering*, 4(1).
- [22] Thiery M., Dangla P., Belin P., Habert G., Roussel N., 2012. Carbonation kinetics of a bed of recycled concrete aggregates: a laboratory study on model materials. WASCON, Gothenburg, SWEDEN.
- [23] Berkely KGC., Pathmanaban S., 1990. Cathodic protection of reinforcement steel in concrete. London: Butterworths & Co. Ltd.
- [24] BB. Hope BB., Alan IPKC., 1987. Chloride corrosion threshold in concrete. *ACI Master Journal*. 84: 306-314.
- [25] Pullar-Strecker P. 1987. Corrosion damage concrete: assessment and repair. London: Butterworths.
- [26] BS EN 14630, 2006. Products and systems for the protection and repair of concrete structures. Test methods. Determination of carbonation depth in hardened concrete by the phenolphthalein method.
- [27] Parrott L.J., 1987. A Review of Carbonation in Reinforced Concrete Building Research Establishment, UK, Waterford.
- [28] Jiang L., Lin B.Y., Cai, Y., 2000. A model for predicting carbonation of high-volume fly ash concrete. *Cement and Concrete Research*, 30(5): 699-702.
- [29] Ceukelaire L.D., Nieuwenburg V.D., 1993. Accelerated carbonation of a blast-furnace cement concrete. *Cement and Concrete Research*, 23(2): 442-452.
- [30] Sanjuan M., Estévez E., Daniel del Barrio AC., 2018. Effect of curing time on granulated blastfurnace slag cement mortars carbonation, *Cement and Concrete Composition*, 90: 257–265.
- [31] Turcry PH., Oksri-Nelfia L., Younsi A., Ait-Mokhtar A., 2014. Analysis of an accelerated carbonation test with several preconditioning, *Cement Concrete Research*, 57: 70–78.
- [32] Chen CT., Ho CW., 2012. Influence of cyclic humidity on carbonation of concrete, *Journal Materials Civil Engineering* 25 (12): 1929–1935.
- [33] Leemann A., Moro F., 2017. Carbonation of concrete: the role of CO₂ concentration, relative humidity and CO₂ buffer capacity, *Materials Structures*, 50(1): 30.
- [34] Gruyaert E., Van den Heede P., De Belie N., 2013. Carbonation of slag concrete: Effect of the cement replacement level and curing on the carbonation coefficient–Effect of carbonation on the pore structure, *Cement and Concrete Composition*, 35 (1): 39–48.
- [35] NF EN 480-1, 2014. Admixtures for concrete, mortar and grout - Test methods - Part 1: reference concrete and reference mortar for testing.