ORIGINAL ARTICLE
DOI: 10.5433/1679-0375.2019v40n2p145

Durability of reinforced concrete under loading condition and curing in marine environment

Durabilidade de concreto armado sob condição de carregamento e cura em ambiente marinho

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Abstract

Many factors can influence the durability of concrete, such as the location to which the material is exposed, the curing, the external environment and the loading action, which can cause micro cracks and/or cracks in the structure. The objective of this study is to verify the relationship between the action of load inducing cracks and the durability of reinforced concrete over two years, submitted to the natural environment and under the action of artificial salt spray. Prismatic specimens were produced and for two years these samples were subjected to artificial salt spray, under the action of permanent central loading and unloaded (reference), with moist curing for 7 days and air-curing, carbonation penetration tests were performed to verify differences between the loading and curing. Crack opening influenced carbonation depth only at 24 months of age. However, these differences are observed in concretes used for air curing. Note that a crack may be a preferred way for CO_2 diffusion to occur within the concrete.

Keywords: Durability. Loading. Cracking. Curing. Carbonation.

Resumo

Muitos fatores podem influenciar a durabilidade do concreto, como o meio ao qual o material está exposto, a cura, o ambiente externo e a ação de carregamento, os quais podem ocasionar microfissuras e/ou fissuras na estrutura. O objetivo deste trabalho foi verificar a relação entre a ação de carregamento induzindo fissuras, a cura e a durabilidade do concreto armado ao longo de dois anos, submetido à ambiente natural e sob a ação de névoa salina artificial. Foram produzidos corpos-de-prova prismáticos e durante o período de dois anos estas amostras foram submetidas à névoa salina artificial, estando sob a ação de carregamento central permanente e sem carregamento (referência), com cura úmida aos 7 dias ou cura ao ar; sendo realizados ensaios de profundidade de carbonatação para verificar diferenças entre as duas situações (com e sem carregamento) e de cura ao longo de dois anos de idade. A abertura de fissuras influenciou na profundidade de carbonatação apenas aos 24 meses de idade; porém, essas diferenças significativas só foram observadas em concretos submetidos à cura ao ar. Observou-se que a fissura pode ser um caminho preferencial para que a difusão do CO_2 ocorra no interior do concreto.

Palavras-chave: : Durabilidade. Carregamento. Fissura. Cura. Carbonatação.

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Introduction

Among the concrete deterioration mechanisms, we can highlight the chemical and physical mechanism. In the physical mechanism, the main causes of the mechanical process of deterioration are overload and cyclic loads; whose main symptom is the cracking in the concrete. This cracking must be controlled due to the risk of reinforcement corrosion, aesthetic appearance and functional requirements such as hygiene (fungal proliferation, microorganisms, etc.) and gas and water permeability.

The Brazilian standard regarding the design of concrete structures NBR 6118 (ABNT, 2014) recommends limits for crack opening, depending on the environmental aggressiveness class. However, there are few Brazilian studies that attest to the real influence of the recommended openings with the durability of reinforced concrete regarding the entry of aggressive agents (chlorides and CO_2) into current work structures. This standard also emphasizes that the actual crack opening limits may not correspond strictly to the estimated values, i.e. actual cracks may eventually exceed these limits.

Regarding the opening, depth and distance parameters of larger and wider cracks and fissures, Frederiksen *et al*. (1997) cited by Hearn and Figg (2001) present a classification for these types of cracks. The number and opening of the micro cracks that may exist in a concrete element depend on the characteristics of exudation, resistance of the transition zone, the cure performed, among other factors.

In addition to cracks, another important factor for concrete durability is curing, which is directly related to evaporation of free water or excess water that has not reacted with cement. With evaporation avoided, the risks of shrinkage on drying are reduced and, consequently, the appearance of micro cracks, which can be used as input to aggressive agents. The intensity of evaporation of free water depends not only on the cure, but also on the composition and temperature of the concrete, the exposed area of the part, the temperature and relative humidity, insulation and wind speed (ARNOLD, 2003; THOMAZ, 2005 AMINI *et al*., 2019).

Materials and methods

The Portland cement used in this experimental work was CP III 40-RS (Portland Blast Furnace cement), whose granular blast furnace slag content can reach 75% NBR 16697 (ABNT, 2018). This cement was used in this study because it is one of the most used in the region, besides the increasing interest in the use of cement with mineral additions (especially blast furnace slag). The following materials were used for the composition of the mixture: river sand (average), available and used in the region of Campinas - SP, crushed stone 9.5 / 25 (B1 - basalt) with a maximum characteristic size of 19mm and polyfunctional additive based of lignosulfonate, with a specific mass of 1.18 g/cm^3.

The experimental mixtures chosen according to the concrete dosage used in this research, whose binder aggregates adopted ratio was 1:5 by mass. In this sense, meeting this requirement, the adopted trait was 1:2:3 (cement: sand: gravel) (in mass), with a water / cement ratio of 0.42, Table 1.

Table 1 – Specification of materials used in the experimental work.

	Cement	Additive	Sand	Gravel	Water
	(Kg/m^3)				
1: 2: 3: 0.42	398	2.4	796	1194	167

Source: The authors.

The choice of ratio (cement: sand: gravel) 1: 2: 3 was due to the adequate mortar content. The water / cement ratio used in this study was adopted in order to obtain more resistant concrete when exposed to aggressive media, according to NBR 6118 (ABNT, 2014).

The consistency index found (according to NM 67, 1998) was 4 ± 1 cm. Consumption of materials used for shaping the specimens and beams can be seen in Table 1, to achieve a fck of 45 Mpa, in compliance with the parameters defined in NBR 12655 (ABNT, 2015) for a very aggressive environment (for a high risk of deterioration - water/cement ratio $\leq$ 0.45 and strength class $\leq$ C40).

Six specimens were molded for each series (a total of 8 series, for ages 6, 12, 18 and 24 months) of prismatic in the dimensions 1.39x0.1x0.1m.

After molding, the prismatic specimens remained in the mold for 48 hours. This period was adopted because it could not be deformed and mainly transport these specimens before 48 hours, as they cracked during handling. After this period, they underwent two types of curing:

a) Ambient or air cure - After demolding, the prismatic specimens were placed outside until the loading date, as observed in Figure 1;

b) Moist cure - After demolding, the prismatic specimens were immersed in lime-saturated water until the age of 7 days.

Figure 1 – Prismatic specimens exposed to the environment and to artificial salt spray.

Source: The authors.

Then the specimens were submitted to two situations:

a) Permanent Central Loading: In this situation a structure was assembled, with the specimens and the supports (cylindrical specimens); gantry placement (threaded bars, steel plates, nuts and washers); application of torque, which caused crack opening within the limits of the norm; annotation of cracks, openings and positioning in the samples; placement on supports (in natural environment and under artificial salt spray) until the date of the tests, with the verification of humidity, temperature and precipitation. Thus one can have situations closer to the reality of works. In addition to the natural environment, NaCl solution was sprayed on the samples simulating a saline mist. This scheme can be observed in Figure 2.

Figure 2 – Gantry mounted for permanent central loading on prismatic specimens.

Source: The authors.

A pilot test was performed on a two-prismatic specimen, applying a concentrated force P until rupture. The first crack (opening within the limits of the norm) occurred with a load of 250 kgf, reaching a torque of 0.5 kgfm, which was monitored throughout the exposure period until the test ages. Loads were constantly gauged with the torque wrench so that they remained constant on the specimen.

b) No Loading: In the second situation, after the wet curing situation, the prismatic specimens were left outside until the test date.

Table 2 shows the sequence adopted for the samples of each molding series, under the different loading conditions and durability testing date.

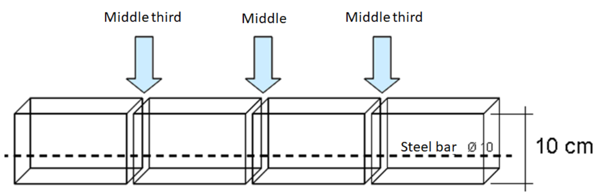
Table 2 – Samples of each molding series, on loading and unloading condition and durability testing dates.

Sample	ASC*	ACCP**	Types of Curing	Testing dates
M6ar	M6arSC	M6arCCP	Air	06 months
M6um	M6umSC	M6umCCP	Moist	06 months
M12ar	M12arSC	M12arCCP	Air	12 months
M12um	M12umSC	M12umCCP	Moist	12 months
M18ar	M18arSC	M18arCCP	Air	18 months
M18um	M18umSC	M18umCCP	Moist	18 months
M24ar	M24arSC	M24arCCP	Air	24 months
M24um	M24umSC	M24umCCP	Moist	24 months

*Unloaded Sample
**Sample under Permanent Central Loading
Source: The authors.

The carbonation depth was verified in ruptured cross sections in the prismatic specimens at the ages of 6, 12, 18 and 24 months. These prismatic specimens were cut at least three locations: in the middle thirds, in the compressed and tractioned areas of the beams, as well as the areas most and least affected by the loads, Figure 3. Using a circular saw, the prismatic specimen was cut to the frame and the rest of the specimen ruptured manually.

Figure 3 – Schematic of the prismatic specimens section.

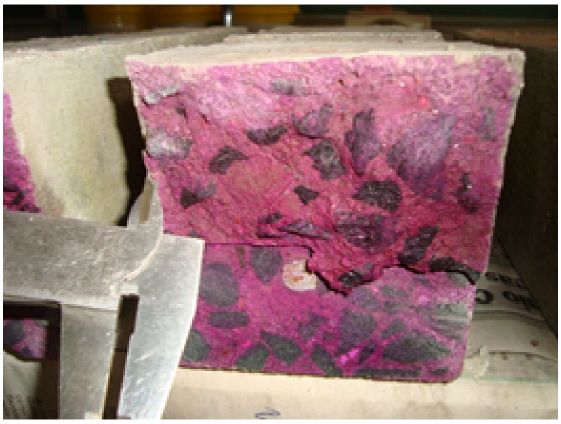


Source: The authors.

To determine the depth of carbonation, a phenolphthalein solution was sprayed, prepared by dissolving 1g of the reagent in 100 ml of ethanol, as recommended by Kasmierczak and Lindenmeyer (1996). After spraying, the carbonated area is colorless and the non-carbonated area is crimson. Prior to performing this test, the fracture surface was cleaned to remove impurities. With the aid of a caliper with 0.5mm accuracy the carbonation depth is read. Generally, a period of at least 10 minutes after phenolphthalein spraying is left to make the area clearer to read.

The step of the test can be observed in Figure 4.

Figure 4 – Durability Tests: Carbonation Depth Reading.



Source: The authors.

Results and discussion

The average carbonation depth results of the prismatic specimens for samples without loading are presented in Table 3.

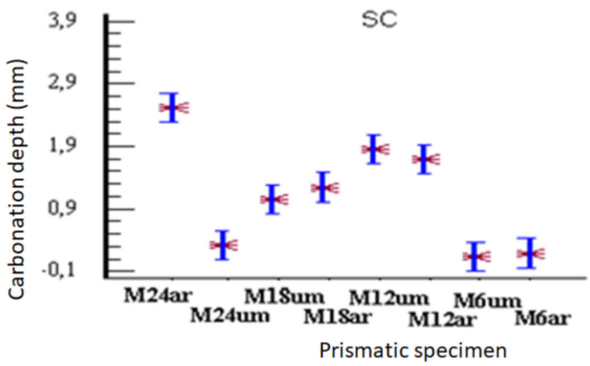
Table 3 – Results of carbonation depth of M6arSC to M24umSC concretes (No Loading).

Sample (SC)	Average (mm)	Standard deviation
M6arSC	0.1	0.2
M6umSC	0.1	0.1
M12arSC	1.7	0.8
M12umSC	1.8	0.5
M18arSC	1.2	0.8
M18umSC	1.0	0.9
M24arSC	2.5	0.9
M24umSC	0.3	0.4

Source: The authors.

It can be seen in Figure 5 the graph with the carbonation depth results for the samples without loading.

Figure 5 – Carbonation depth for unloaded samples.



Source: The authors.

Higher carbonation depth results were observed for the M24arSC and M12umSC samples, and the M24arSC sample presented higher level of dispersion of the results.

Table 4 shows the comparisons between the results of carbonation depth of the unloaded concretes in relation to the type of cure (wet and air cure at the different test ages).

In the comparisons between the mean carbonation depth results of the unloaded prismatic specimens submitted to air curing, it was observed that at 18 and 24 months of age the values were higher than those submitted to wet curing. However, the significant difference between the results occurred only at 24 months, where the carbonation depth for air-cured concrete (M24arSC) was significantly higher than that of wet cured concrete (M24umSC).

At 12 months of age, the carbonation depth value of the wet curing sample (M12umSC) was slightly higher than the air curing sample (M12arSC), however, this difference was not significant. At 6 months of age the results of carbonation depth of the concrete submitted to the curing types (air and wet at 7 days) were the same.

In the situation where the concretes were not subjected to loading, there were only statistically significant differences in carbonation depth results at 24 months of age. At other ages, cure did not influence the difference in sample results.

In this sense, it can be said that the cure did not influence with significant differences the carbonation depth until 18 months old. Only at 24 months did the carbonation depth values of concretes subjected to air cure were significantly higher than those of concretes subjected to wet cure. However, other factors may also have influenced this result, such as the environmental aspects to which the samples were submitted. In this case, one should consider the slow advancement of carbonation depth, as observed by Bourguignon (2004).

In concretes without cracks, the aggressive agent transport process depends largely on the connectivity between the pores and their size. With cement paste hydration, connectivity and pore size tend to decrease. Some factors such as water / cement ratio are fundamental to have a pore segmentation with cement hydration. As in this research the water / cement ratio is low, pore disconnection can be achieved with adequate cure (IRASSAR, 2004; LI; LI, 2019). In this sense, the importance of healing is seen in order to achieve better durability results at older ages.

Table 4 – Comparison between carbonation depth results of unloaded concretes (SC).

Sample	Type of Curing	Test Age	Difference Between Carbonation Depth Results
M6arSC-M6umSC	Air cure (ar)-Moist cure for 7 days (um)	6 months	No*
M12arSC-M12umSC		12 months	No**
M18arSC-M18umSC		18 months	No***
M24arSC-M24umSC		24 months	Yes****

*(Carbon. Depth. ar = Carbon. Depth. um)
**(Carbon. Depth. ar < Carbon. Depth. um)
***(Carbon. Depth. ar > Carbon. Depth. um)
***(Carbon. Depth. ar > Carbon. Depth. um)

Source: The authors.

The average carbonation depth results of concretes under permanent central loading are presented in Table 5.

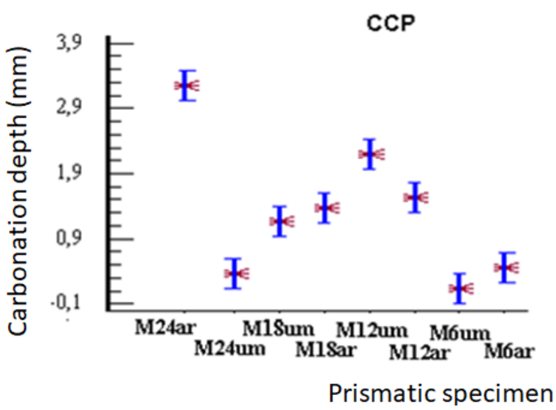
Table 5 – Results of carbonation depth of concretes under permanent central loading (PCC).

Sample	Average (mm)	Standard deviation
M6arCCP	0.4	0.5
M6umCCP	0.1	0.0
M12arCCP	1.5	0.9
M12umCCP	2.1	0.7
M18arCCP	1.3	1.3
M18umCCP	1.1	0.8
M24arCCP	3.2	1.1
M24umCCP	0.3	0.6

Source: The authors.

The graphs showing the carbonation depth results can be seen in Figure 6.

Figure 6 – Carbonation depth results of concretes subjected to permanent central loading (CCP).



Source: The authors.

When relating the carbonation depth to the axial compressive strength of concrete, some studies, such as Costa Junior *et al*. (2005) and Silva (2007), found that this depth tends to decrease with increasing strength class, especially when concreting using cements with high blast furnace slag content; However, in this study this trend was not observed.

Carbonation results with permanent central loading reached a maximum of 3.2 mm when air cured and 2.1 mm wet cured for 7 days. In this sense, attention is paid to the importance of curing in the early ages of concrete, so that the covering established by NBR 6118 (ABNT, 2014), of the order of 30 mm, is sufficient to guarantee the durability of the concrete, under these conditions. subject to continuous loading or cracking within the parameters of this standard. Care in the steps of the concrete production process (dosing, mixing, casting, thickening and curing) should be taken into account in this context.

The following is a comparison between the samples at their respective exposure ages (different test ages - 6, 12, 18, and 24 months) with the types of cure used in this research (normal cure and air cure), Table 6.

In this context, it can be said that at 6 and 18 months the cure did not influence the depth of carbonation, despite the fact that the results of concrete cured to air were higher than those submitted to wet curing, there were no significant differences between the results. At 12 months, there was a small significant difference between the results, indicating that the carbonation depth in the air-cured concretes was slightly smaller than the wet cured concretes. In this case, there was an exception, since at other ages the depth of carbonation was greater for the air-cured samples compared to the wet curing. In the case of samples at 24 months, the difference between the results was greater,

Table 6 – Comparison between the results of carbonation depth of concretes submitted to permanent central loading (PCC).

Sample	Type of Curing	Test Age	Difference Between Carbonation Depth Results
M6arCCP-M6umCCP	Air cure (ar)-Moist cure for 7 days (um)	6 months	No*
M12arCCP-M12umCCP		12 months	Yes**
M18arCCP-M18umCCP		18 months	No***
M24arCCP-M24umCCP		24 months	Yes****

*(Carbon. Depth. ar > Carbon. Depth. um)
**(Carbon. Depth. ar < Carbon. Depth. um)
***(Carbon. Depth. ar > Carbon. Depth. um)
****(Carbon. Depth. ar > Carbon. Depth. um)

Source: The authors.

since the concrete cured with air curing had a carbonation depth of 3.2 mm and wet curing of 0.3 mm; probably due to the period that these concretes were exposed outdoors, influencing the carbonation depth results.

When analyzing the influence of climate on the carbonation depth of specimens submitted to the external environment during the test period, it can be verified that the relative humidity (RH) in the years 2008 and 2009 was in the range of 70%, that is, an environment that is between 60% and 80%, where the highest degree of carbonation and deleterious depassivation occurs significantly (ABCP, 1999; SALES; GOMES, 2004). However, this is not the only environmental factor that provides a conducive way to carbonation, because temperature and precipitation, which were measured in the two years in which the samples were exposed and had their variations depending on the period of the year. Higher rainfall between November and March and drier periods between April and October are also factors that influence carbonation. The temperature ranged between 17 °C and 26 °C, which can be considered a high variation and the precipitation also varied a lot depending on the time of year.

Finally, from the environmental point of view, these factors contributed to the occurrence of carbonation. Despite the maximum and minimum peaks in both temperature and relative humidity, it is observed that climate was an important factor to be analyzed.

Table 7 shows the comparisons of the average carbonation depth results of the loading and unloading samples used in this study (PCC) for each sample at the different ages tested when subjected to wet curing for 7 days.

Table 7 – Comparison between the results of carbonation depth of concretes submitted to permanent central loading (PCC).

Sample	Test Age	Difference Between Carbonation Depth Results
M6umCCP-M6umSC	6 months	No*
M12umCCP-M12umSC	12 months	No**
M18umCCP-M18umSC	18 months	No***
M24umCCP-M24umSC	24 months	No****

*(Carbon. Depth. CCP = Carbon. Depth. SC)
**(Carbon. Depth. CCP > Carbon. Depth. SC)
***(Carbon. Depth. CCP > Carbon. Depth. SC)
****(Carbon. Depth. CCP = Carbon. Depth. SC)

Source: The authors.

Table 8 shows the comparisons of the average carbonation depth results of samples under permanent loading (PCC) and uncharged at different ages tested under air curing.

Table 8 – Comparison between the carbonation depth results of the specimens submitted to the type of loading (CCP) and unloaded (SC), in air cure.

Sample	Test Age	Difference Between Carbonation Depth Results
M6arCCP-M6arSC	6 months	No*
M6arCCP-M6arSC	12 months	No**
M18arCCP–M18arSC	18 months	No***
M24arCCP–M24arSC	24 months	Yes****

*(Carbon. Depth. CCP > Carbon. Depth. SC)
**(Carbon. Depth. CCP < Carbon. Depth. SC)
***(Carbon. Depth. CCP > Carbon. Depth. SC)
****(Carbon. Depth. CCP > Carbon. Depth. SC)

Source: The authors.

At almost all ages of testing and curing, concretes subjected to permanent central loading had greater carbonation depth than unloaded concretes, with the exception of air-curing concrete at 12 months and wet curing at 6 months. Despite the observed in the concretes studied here, in which the carbonation depth was greater in concretes under permanent central loading only at 24 months, and under air curing, there was a significant difference between the results, that is, only at two years of age and in concretes undergoing air curing, the crack opening influenced the result of carbonation depth.

Charging and exposure time interfere with the results, a fact observed by Castel *et al*. (1999), who verified the influence of charging intensity on CO_2 penetration. It was observed that up to 18 months of age and with the induced crack opening, there were no significant differences in the carbonation depth results.

Another factor that should also be taken into consideration in this context is the importance of adequate cover thickness to ensure the durability of the structure, as recommended by NBR 6118 (ABNT, 2014) and Martins (2001) guidelines.

Generally speaking, the exposure of concrete for a period of one year is a relatively short time to obtain significant differences and significant carbonation depth data, especially when there are studies with samples subjected to natural carbonation, without artificial acceleration processes. More expressive results begin to occur after one year of age, with greater differences in older ages with samples subjected to air curing, as found in the last tests performed at 24 months of age.

As mentioned in the literature, some factors are necessary for concrete deterioration due to the entry of aggressive agents (such as CO_2), which are related to the variables of this study, such as the stages of the production process (cure), the conditions of the external environment (humidity and temperature), surface cracks in the material and material quality (WIN *et al*., 2004; SHEN *et al*., 2019). From these factors the concentration of aggressive agents in concrete can be higher or lower. In the case of this study, it is seen that the crack factor was important for greater carbonation depths, allied to the environment and cure, besides the material quality and its properties.

A problem arising from cracking by loading action is the interconnection of the pores and capillaries of the mixture thus increasing the permeability of the concrete. This permeability, due to cracks and micro cracks in the paste, allows more water or aggressive chemical ions to penetrate the structure, facilitating deterioration (WANG *et al*., 1997; GERARD; MARCHAND, 2000).

Conclusions

Crack opening influenced carbonation depth only at 24 months of age; However, these significant differences were only observed in concretes subjected to air curing. Thus, from the macro point of view, it can be noted that cracking may be a preferred way for carbon dioxide diffusion to occur within the concrete, but this process occurs slowly inside the crack, since we did not observed the influence of cleft on carbonation depth at 6, 12 and 18 months.

When comparing the crack opening tolerances of the Brazilian standard to the American Concrete International code (ACI 318-89), which limits crack opening of 0.4 mm, it is found that the allowed openings for the Brazilian standard are much larger (WANG *et al*., 1997). Although climatic conditions in Europe, for example, are much worse than in Brazil, where there are temperatures ranging from -5 °C to 30 °C. In the case of France and in Brazil there are variations that range from 20 °C to 35 °C. However, it is clear that technological control of material quality and execution in Brazil tends to be less strict, thus crack openings can be aggravating in this context. On the other hand, it is observed in this study that in the Brazilian climatic situations, until the age of two years there were no significant differences between the results of samples under the loading condition determined in this study, i.e. no loading.

Studies on the influence of cracking in Europe adopt longer test periods, which reach up to 17 years of exposure of the specimens and it appears that this longer period is necessary to obtain more expressive results regarding the influence of the crack opening in the durability of reinforced concrete (VIDAL *et al*., 2007; FRANÇOIS *et al*., 2006).

In the case of cure, its influence was observed from 12 months of age, especially in the concrete under load (PCC). However, in general terms, only at 24 months of age was the influence of cure on carbonation depth in all situations studied (with and without loading). In this sense, the importance of curing is seen in the durability of concrete, especially when using cement with mineral additions. However, the cure only begins to influence the carbonation depth at older ages, since in unloaded concretes (reference) its influence was only observed at 24 months of age.

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Received: Sept. 13, 2019
Accepted: Nov. 16, 2019