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ORIGINAL ARTICLE

Proposed variations in nominal reinforcement cover based on the environmental aggressivity class (EAC) of concrete exposure

Proposição de variação do cobrimento nominal das armaduras baseada na classe de agressividade ambiental (CAA) de exposição de concretos

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Abstract: The physical and chemical protection of steel reinforcement afforded by the cover is a consequence of the quality of the concrete and its thickness, with a long-term impact on durability and service life. This study proposed variations in cover based on environmental aggressivity class (EAC) of exposure considering concretes of prescribed compressive strength classes (C20/C25/C30/C40). To this end, concrete mixtures were subjected to accelerated testing in salt spray chambers or carbonation. Accelerated testing was kept for periods long enough to reach each EAC cover level. Thus, the effect of each EAC, from mild to severe, was determined on the physical and mechanical characteristics of each mixture. It was determined that the required reinforcement cover varied linearly with compressive strength. This denoted the possibility of using more than one class of concrete and cover for each EAC. It should be noted that the difference in required cover became greater when using concrete with a strength class higher than C30. Still, it was noticed that the chloride ions attack s was more severe than carbonation and was, for most of the test cases, the determinant factor in minimum cover thickness to ensure the desired durability.

Keywords: salt spray, carbonation, recovering, durability.

Resumo: O cobrimento das armaduras tem a função de proteger física e quimicamente as armaduras de aço, através da qualidade do concreto e sua espessura, influenciando na durabilidade e vida útil. Este trabalho propôs variações do cobrimento baseados na classe de agressividade ambiental (CAA) de exposição dos concretos, considerando a resistência especificada em cada classe. Os traços foram submetidos aos ensaios acelerados de névoa salina e de carbonatação. Os testes foram mantidos por períodos até que o cobrimento de cada CAA fosse atingido, determinando o impacto no cobrimento das armaduras para cada CAA, mais amena ou mais severa. Cada um destes traços foi avaliado quanto às características físicas e mecânicas. Verificou-se que o cobrimento necessário às armaduras varia de maneira linear com a resistência à compressão dos traços, denotando a possibilidade de considerar mais de uma classe de resistência de concreto e o cobrimento nas diferentes CAA. Destaca-se que a diferença do cobrimento necessário em relação às CAA se torna maior quando utilizados concretos de classe superior a C30. Ainda, percebeu-se que o ataque por íons cloreto é mais severo que a carbonatação, tendo determinado, na maioria das verificações, a espessura mínima de concreto para garantir a durabilidade almejada.

Palavras-chave: estruturas, concreto armado, durabilidade, cobrimento das armaduras.

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1 INTRODUCTION

Wally et al. [1] stated that structural deterioration was mainly due to carbonation, and the early decrease in the service life of structures was a global concern. Durability is a parameter that relates several characteristics to a structure, each with an individual response to exposure to aggressive environmental factors [2]. There are several reasons to attain improved durability, but a driving motivation is the environmental impact and elevated use of raw materials in the cement industry [3]. Additionally, De Schutter [4] considered early concrete degradation gravely damaging to the environment. The leading cause of degradation in reinforcement is corrosion due to the depassivation of the protective concrete layer from carbonation and/or the chloride ions [5]. In the Tuutti [6] model, degradation started from the initial penetration or propagation of these agents and was affected by temperature, humidity, and oxygen content.

Brazilian standards contain design and specifications of structures to ensure a level of durability and service life ([7], [8] and others), which are similar to international standards [9]–[12]. These contain minimum parameters of cement consumption, water cement (w/c) ratio, nominal cover for reinforcement, and compressive strength based on the environmental aggressivity class (EAC). While EACs are defined in standard ABNT NBR 6118 [7], it does not consider particular micro and macroregional effects on EACs and the material's durability. Also, it is not clear, according to the standard, how these parameters can be related to the durability expectation, considering the main aggressiveness agents in Brazil (CO_2 and Cl-). Understanding the behavior of concrete mixes according to their composition and relationship with durability can provide greater assertiveness in the concrete specification.

Standard ABNT NBR 6118 [7] designated rural zones or submerged environments as EAC I with low aggressiveness. Rural zones had a low potential due to reduced emissions of pollutants, fossil fuel combustion, presence of industries, and other factors [13], while submerged environments had pores filled with water which prevented or impeded the ingress or aggressive agents. Moderately aggressive EAC II revolved around urban zones with a low risk of structural deterioration for the given concentration level of CO_2. Highly aggressive EAC III was for buildings located in marine or industrial environments with a high risk of deterioration. Helene [13] noted that the speed of corrosion in a marine environment could be 30x to 40x that of a rural zone. Industries grouped in EAC III also included those with lower aggression potential, such as mechanical, dairy, or food. The highly aggressive EAC IV corresponded to structures with elevated risks of deterioration in industrial environments or directly exposed to salt spray. Industrial activities in this class included aggressive chemicals, industrial storage tanks, electrophoretic deposition (EPD), and others [13].

Concerning other classifications, standard EN 1992-1 [14] determined the aggressiveness class for the structure's physical and chemical exposure characteristics and the mechanical wear and tear. The aggressiveness classes were based on standard EN 206-1 [11], which considered only environmental risks. The Australian standard AS 3600 [9] presented five aggressiveness classes: A1, A2, B1, B2 and C; each with minimum fck requirements and concrete reinforcement cover. Similarly, the Indian standard IS 456 [10] contained mild, moderate, severe, severe, and extreme aggressiveness classifications, along with maximum w/c ratios and minimum cement and concrete fck to ensure a durable structure. There were similarities between standard ABNT NBR 6118 [7] and the Indian and Australian standards in that aggressiveness levels were classified from mild to intense without direct specification of the deterioration agents. In addition, AS 3600 [9] presented the effect of concrete compressive strength on minimum cover, which provided designers with more flexibility.

An analysis of the mechanisms of deterioration denoted the importance of concrete's chemical and physical protection to the steel reinforcement. This is guaranteed by its quality and thickness [15]. To evaluate the behavior and durability of concrete, theoretical models were used to predict service life. These mathematical models replicated natural, physical, and chemical phenomena and their occurrence based on one or more characteristics of the concrete. Theoretical carbonation models varied in input data. The Hamada [16] model required characteristics of the concrete such as type of aggregate, type of cement, and the use or not of chemical additives to estimate the carbonation depth. Pacheco [17] noted that the Hamada [16] model did not consider external factors such as local aggressiveness, temperature, relative humidity and others but was simpler to apply. In terms of the chloride ion front, Pacheco [17] identified several theoretical models, such as Clear and Hay [18] and Bob [19]. These models consider the concrete characteristics and a degree of generalization concerning the concentration of Cl- in the environment and reinforcement cover.

Brazilian standards did not define the relationship between parameters such as fck, w/c ratio, cover, and cement consumption which affected the specifications of a structural element. In addition, no flexibility was given to stated values that would degrade the durability or safety of the structure. De Schutter [4] noted the necessity to have criteria defining durability standards for concretes not previously listed in standards, eliminating the need to conduct tests or comparative studies.

Thus, to relate concrete specifications to the durability of a structure, this study tested the response of different concrete mix ratios with recommended characteristics from standards ABNT NBR 6118 [7] and ABNT NBR 12655 [8] to accelerated EAC tests. Theoretical models were used as a guide for the experimental tests, and the effect on reinforcement cover of a specific type of concrete assigned to mild or intense EAC was evaluated. The aim of this study is to provide theoretical and experimental relations between concrete characteristics and the EAC.

2 METHODOLOGY

Testing consisted of 4 stages. Stage I defined carbonation depths with the Hamada [16] model with different w/c ratios for each EAC, while the chloride ion front was defined from the Clear and Hay [18] model. The models were chosen because they allow a certain degree of generalization, considering the concrete characteristics as the variation data. The time was set as 50 years, considered a durability requirement. Stage I also determined the characteristics of the materials used in the study. Stage II produced the mix ratios per standards [7,8] with minimum cement use, w/c ratio, and fck for each EAC. In the mix ratios, the mortar and superplasticizer additive contents were fixed at 56% and 0.87%, respectively, with respect to the mass of cement. The measured slump for all composites was classified as S100 as per standard ABNT NBR 8953 [20]. Stage III conditioned samples before accelerated testing by subjecting the four proposed concrete mixtures to attack cycles until the theoretical values for each carbonation and chloride ion penetration fronts were reached. Following conditioning, further accelerated testing was conducted until carbonation and chloride attack values reached each EAC. The depth of penetration of each attack was measured, and each concrete mixture's physical and mechanical characteristics were evaluated to determine the nominal reinforcement cover.

2.1 Theoretical model predictions of service life and application to EAC (Stage I)

Theoretical model predictions of service life were calculated with respect to carbonation and chloride ion attack fronts. These used concrete specifications for each EAC presented in standards ABNT NBR 6118 [7] and ABNT NBR 12655 [8]. The carbonation depth predictions were based on the Hamada [16] model with w/c ratio as the variable of each mixture. Results are shown in Table 1 for a 50-year period for each of the four concrete mixtures used in this study. The coefficients considered the type of cement (Ra), type of aggregate (Rc), and use of additives (Rs). Further details on these mixtures can be found in Pacheco [17]. The Cl- penetration fronts were based on the Clear and Hay [18] model, and the results are shown in Table 2.

Table 1 – Service life prediction from the carbonation depth of the Hamada [16] model.

Property	Concrete Mixture			
	T1	T2	T3	T4
w/c ratio	0.65	0.60	0.55	0.45
Ra coefficient	1	1	1	1
Rc coefficient	0.6	0.6	0.6	0.6
Rs coefficient	0.4	0.4	0.4	0.4
R = (Rc x Rs x Ra)	0.24	0.24	0.24	0.24
Calculated cover (mm)	7.0	6.5	5.5	3.9

Table 2 – Service life prediction from chloride attack front of the Clear and Hay [18] model.

Property	Mixture			
	T1	T2	T3	T4
w/c ratio	0.65	0.60	0.55	0.45
Chloride concentration*	5%	5%	5%	5%
Estimated period (years)	50	50	50	50
Calculated cover (mm)	14.3	13.4	12.4	10.5

*chloride concentration defined in ASTM B-117 [21].

2.2 Characterization of Mixtures (Stage II)

The characteristics of each concrete mixture are shown in Table 3.

Table 3 – Characteristics of each concrete mixture of this study.

Property	Mixture			
	T1	**T2**	**T3**	**T4**
w/c ratio	0.65	0.60	0.55	0.45
Mortar content	0.57	0.57	0.57	0.57
Cement usage (kg/m^3)	260	280	320	360

Each concrete mixture was characterized with respect to physical and mechanical properties. The slump test, performed following standard ABNT NBR 16889 [22], determined all mixtures as class S100. Compressive strength tests were conducted at 7 days, 28 days, 56 days, 84 days, and 140 days per standard ABNT NBR 5739 [23], with three samples for each age. Water absorptivity, void index, and specific mass were measured at 7 days and 28 days following standard ABNT NBR 9778 [24], using three samples for each trace. Capillary absorption was determined at 1 min, 2 min, 3 min, 4 min, 5 min, 10 min, 15 min, 30 min, 1 h, 2 h, 3 h, 4 h, 5 h, 6 h, 24 h, 48 h, 72 h, and 96 h from the procedures of standard RILEM TC 116 PCD [25], with three samples for each trace, as the other tests. Concrete porosity was determined from mercury intrusion at 84 days, with one sample for trace measuring 5 x 20 mm extracted from the mixtures and dried in an oven until mass stabilization. The testing equipment measured pores from 200 µm to 0.0070 µm from varying pressure.

2.3 Cycles of attack from aggressive agents and necessary cover (Stage III)

The aggressive agents used were CO2 and Cl-. Concrete test samples were plaques measuring 40 x 40 x 160 mm cured for 28 days. Following curing, conditioning was performed based on the methodology of RILEM TC 154 EMC [26] adapted by Pacheco [17]. Accelerated carbonation was induced in an air exchange-capable chamber with a 3% CO_2 concentration and relative humidity of 70%. The test chamber was used for 2 purposes: to determine the period at which aggression fronts reached levels predicted by theoretical models and to determine the necessary cover of all mixtures for this period. The evaluation was conducted by spraying a phenolphthalein solution in 1% concentration on a transversal slice of each sample. Each evaluation was conducted 3 times and averaged. Figure 1 shows the use of phenolphthalein solution and the measurement of carbonation depth, respectively.

Chloride ion attack procedures followed recommendations from standard ASTM B117 [21]. A sodium chloride (NaCl) solution with a concentration of 5% was applied in a saturated environment kept at 35 ºC. The pH of the saline solution spray was between 6.5 and 7.2. Samples were cured for 28 days and conditioned for 56 days prior to testing. The chloride front was evaluated with a silver nitrate (AgNO3) spray. Figure 2 shows the salt spray chamber. The base and top of the plaques were sealed with epoxy-based paint applied in 3 coatings as instructed by Rissardi et al. [27]. To further differentiate the grey and brown tonalities of the silver nitrate marker, images were digitally post-processed on Arc Map 10.3 software. Further details on the methodology can be found in Pacheco [17]. To guarantee the number of samples enough to perform the tests, for each composition, ten samples were submitted to carbonation and ten samples were exposed to salt spray.

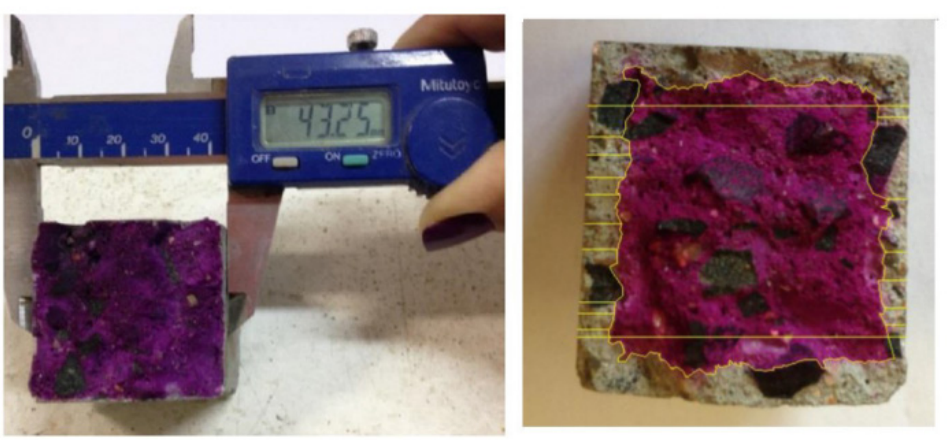

Figure 1. Carbonation depth mensuration with phenolphthalein solution.

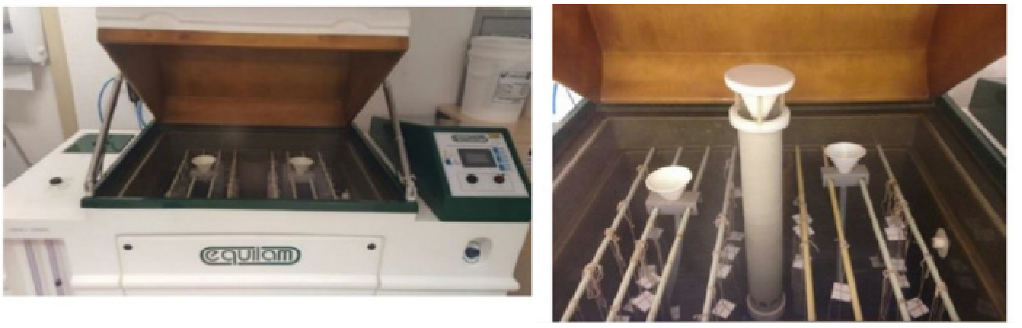

Figure 2. Salt spray chamber.

2.4 Materials

The cement used in this study was CP-V ARI. The blaine test result was 4875cm^2/g and the specific mass was 3.0049 g/cm^3. The superficial area through BET method was 2.0474 ± 0.0085 m^2/g. The characteristics diameters were: D10: 13,08µm, D50: 46,34 µm and D90: 87,99 µm. Fine aggregate was quartz river sand with apparent density of 1.37 g/cm^3, maximum diameter of 2.4 mm and fineness modulus of 1.85. Coarse aggregate was basaltic with apparent density of 1.54 g/cm^3, maximum diameter of 12.5 mm and fineness modulus of 6.73. A 3rd generation, polycarboxylate ether-based superplasticizer was also added at 0.87% content with respect to the mass of cement. The mixtures were made with a horizontal mixer. More material and procedure details can be found in Pacheco [17].

3. RESULTS

3.1 Compressive strength

Potential compressive strength results are shown in Figure 3.

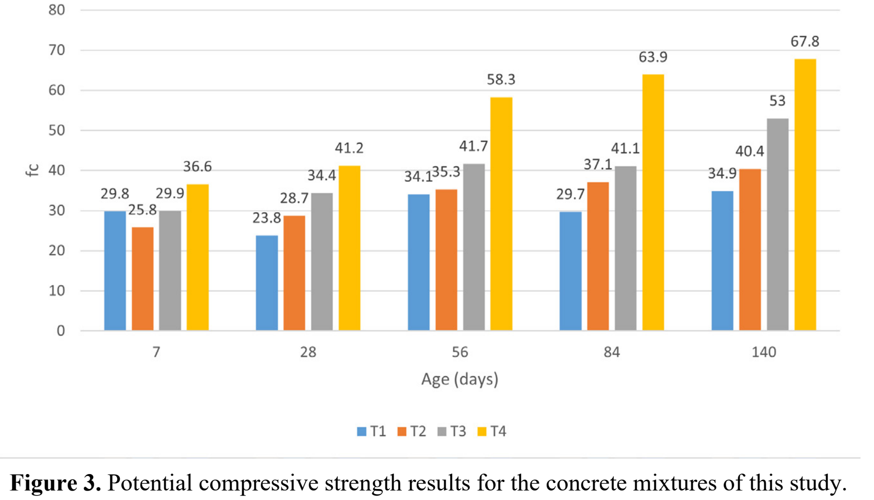

Figure 3. Potential compressive strength results for the concrete mixtures of this study.

Figure 3 shows that the compressive strength of mixture T1 oscillated with decreases at 28 days and 84 days. This discrepancy could be the result of improper test procedures, irregularities in the shaping of the samples (non-parallel surfaces), or mistakes in the molding process. Those improper procedures may also explain the higher value in Mixture T1 in comparison with Mixture T2 at 7 days. Mixture T2 had a gradual increase in strength, with the final value at 140 days 56.3% higher than at 7 days. Mixture T3 increased 18.9% between 7 days and 28 days, with a slight reduction at 56 days and an increase up to 140 days. Mixture T4 had a constantly increasing strength over time and had the highest values at any given age amongst all concretes. As much as there are variations in the presented values, it must be considered that the potential values are being exposed, which can highlight the difference between the traits, for example, if compared with the average values. For more information, consult Pacheco [17].

It was noted that all concrete mixtures had their initial and final behavior following predictions from standards with a linear increase with respect to cement usage and a proportional decrease with respect to w/c ratio from T1 to T4. This relation between strength, cement usage and w/c ratio was discussed by Andrade and Tutikian [28]. Mixtures T3 and T4 had the best strength behavior and would be recommended for use in environments with greater aggressiveness, leading to possible improved durability due to lower porosity [29]. Yasin et al. [30] noted that high initial strength cements frequently achieved the estimated strength by 14 days but, in the case of the concretes of this study, compressive strength continued to develop even at 140 days.

3.2 Physical properties

Physical properties of the concrete mixtures are shown in Table 4.

Table 4 – Average physical properties of concrete mixtures of this study.

Concrete	Water absorption (%)		Void index (%)		Specific mass (g/cm^3)	
	7 days	28 days	7 days	28 days	7 days	28 days
T1	6.10	4.56	13.47	10.19	2.55	2.49
T2	6.02	4.82	13.22	10.70	2.53	2.49
T3	4.98	4.61	11.31	10.46	2.56	2.54
T4	4.73	4.79	10.88	10.96	2.58	2.57

Table 4 shows that, at 7 days and as expected, water absorption decreased linearly as cement usage increased for each concrete mixture, due to higher fine content and concrete compactness [28]. Mixture T4 had the largest fck and lowest water absorption, detaching the relation between mechanical and physical properties [15]. The total decrease in water absorption was 22% from mixture T1 to T4, while the corresponding decreases from T1 to T2 and T1 to T3 were 1.3% and 18.4%, respectively. This linear decrease in water absorption was no longer present at 28 days and instead, no discernible trend was noted. The largest value of water absorption at 28 days was observed for T2 and the standard deviation of the values was of 0.13%. These results were in contrast to the predictions of Medeiros-Junior et al. [31].

Specific mass results presented an increasing trend with respect to increasing compressive strength with respect to curing age for all concrete mixtures, considering that the hydration of the cement happens progressively, improving the matrix density. The exceptions to this trend were for T2 at 7 days and 28 days. The differences in specific mass remained below 0.08 g/cm3 and the standard deviations were of 0.021 g/cm^3 and 0.039 g/cm^3 at 7 days and 28 days, respectively. As noted by Isaia [32], void spaces decreased compressive strength. Additionally, the presence of void spaces also decreased specific mass, so it was possible to correlate specific mass to compressive strength, and such was the case for the data at 7 days.

Capillary water absorption was measured at 28 days and 84 days. Absorption and saturation rates for all concrete mixtures at each age are shown in Figures 4 and 5. Figure 4, at 28 days, shows uniformity in results and higher inclinations for the absorption and saturation curves of T1 and T2 over T3 and T4. Analyzing the results, concrete mixtures with lower compressive strength had higher capillary water absorption both in absorption and saturation. This relation was reported by Isaia [32] and was noted in the total water absorption test at 7 days. The coefficients of determination for absorption and saturation curves were of 0.84 and 1.00, respectively, and indicated a good correlation between the data points and curve fit equations at 28 days.

The capillary water absorption results of Figure 5 at 84 days presented similar trends as Figure 4 at 28 days. A linear behavior was observed in each concrete mixture, but the saturation curves were more evenly spaced. The coefficients of determination for the saturation curves were between 0.88 and 1.00. Thus, the behavior at 84 days is similar to what was obtained for total water absorption at 7 days.

The mix ratios used were in accordance with EAC parameters from standards ABNT NBR 6118 [7] and ABNT NBR 12655 [8] to ensure projected service life periods. Results showed that porosity levels were in accordance to this objective: mixtures recommended for more aggressive environments presented lower capillary water absorption from the prescribed w/c ratio and cement usage. Thus, although there are no performance specifications in Brazilian standards, equivalent results for external aggression could be obtained from prescribed capillary absorption of permeability standards.

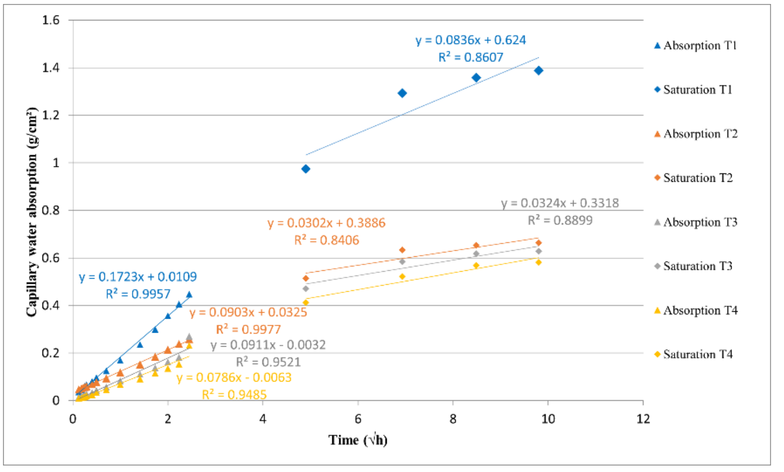

Figure 4. Capillary water absorption at 28 days for the concrete mixtures of this study.

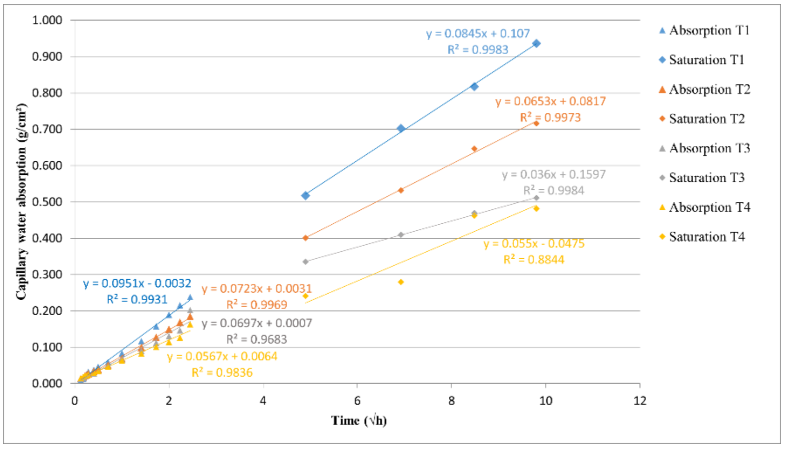

Figure 5. Capillary water absorption at 84 days for the concrete mixtures of this study.

Table 5 – Comparison of effective capillary water absorption and total water absorption at 28 days of curing.

Concrete	Effective capillary water absorption ($g/cm^2.\sqrt{t}$)	Total water absorption (%)
T1	0.080	4.56
T2	0.091	4.82
T3	0.091	4.61
T4	0.079	4.69

Table 5 presents a comparison of capillary water absorption and total water absorption at 28 days of curing. Results show no discernible trend with respect to the concrete mixture. Capillary absorption presented peak values for T2 and T3, while total water absorption peaked with T2 and T4. These contrasted the expected result of decreased absorption rates as strength increased. The differences between the properties should also be stressed: total absorption alluded to the test body and was sensitive to molding and void spaces regardless of distribution, while capillary absorption related to the distribution and connection of pores which affected the ingress of aggressive agents.

Comparing compressive strength and capillary absorption at 84 days noted a trend of increasing strength for T1 and T4, which correlated to a decreasing capillary absorption trend for the same concrete mixtures. The inverse proportionality between these two properties was expected from previous studies [31]. Zhang and Zong [33] compared the same properties and determined a relation between compressive strength and capillary absorption with R^2 of 0.70. Bozkurt and Yazicioglu [34] evaluated the effect of time on these properties. They noted that, at advanced ages, there was a combined decrease in capillary absorption and improvement in mechanical properties, which further corroborated the results of this study.

3.2.3 Mercury intrusion porosimetry (MIP)

Figure 6 shows the results of accumulated volume of mercury (cm^3/g) and distributed intruded volume (cm^3/g) in samples of each concrete mixture with respect to pore diameter.

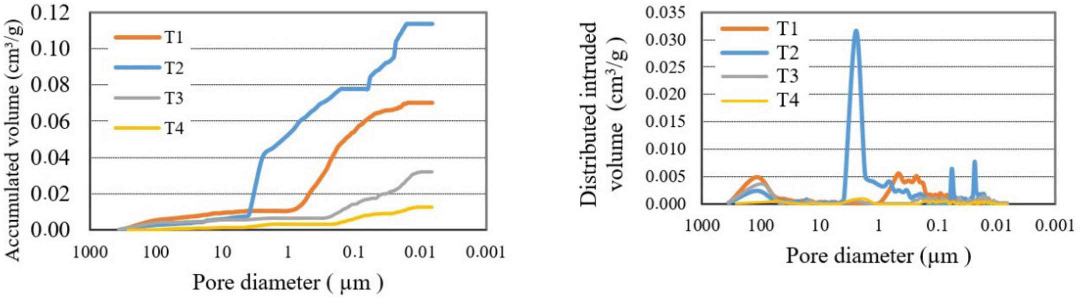

Figure 6. Accumulated and distributed intruded volumes from MIP with respect to pore diameter.

Figure 6 shows that the most significant intruded volume occurred for T2. At the same time, the remaining concrete mixtures followed a relationship between compressive strength and porosity with T4 presenting the least quantity of pores and intruded volume. Comparing these mixtures, the intruded volume of mercury of T4 was 11% lower than T2. This was in contrast to the results of Mehta and Monteiro [35], which expected that the most significant volume of mercury would occur for T1 as it had the minor compressive strength. In addition, the distribution of intruded mercury occurred mostly in pores of less than 0.1 µm. However, T2 presented a peak in pores between 1 µm and 10 µm which indicated a different characteristic of this mixture both with regards to pore distribution and total porosity. Nonetheless, results for T1, T3 and T4 were in agreement with Mehta and Monteiro [35] with porosity inversely proportional to compressive strength. Andrade and Tutikian [28] noted that total porosity had less of a relation with mechanical strength when compared to the distribution and size of pores – factors that depended on w/c ratio and the mixture's hydration level.

According to the classification proposed by Helene [13], most of the volume of intruded mercury occurred in pore diameters between 0.1 µm and 1,000 µm and indicated capillary absorption. Consequently, the intruded mercury volume in pores was compared to the capillary absorption data at the same 84 days when MIP was conducted and the results are shown in Figure 7.

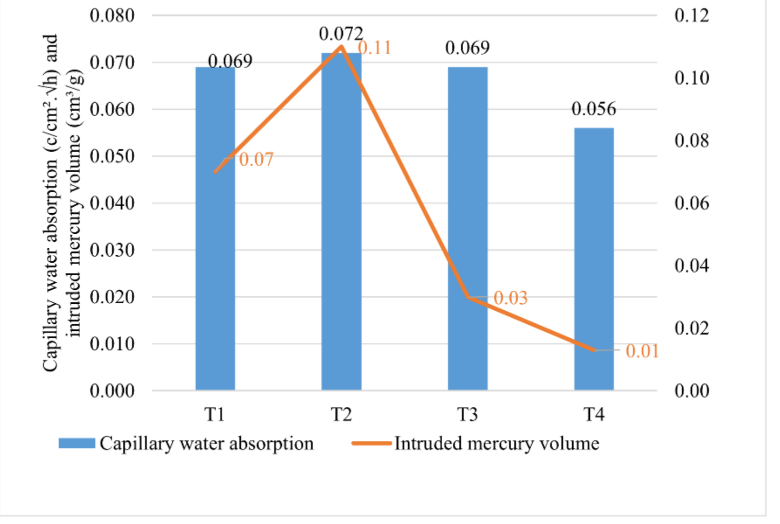

Figure 7. Comparison of capillary water absorption and accumulated mercury volume.

As seen in Figure 7, concrete mixtures T3 and T4 had the least capillary water absorption and the least volume of intruded mercury in the pore size range between 0.1 µm and 1,000 µm. Nonetheless, results for these two mixtures still suggested a relation between pore volume, capillary absorption, and the linear relation between these variables [33]. On the other hand, T2 presented a distinct behavior with a larger volume of intruded mercury despite having a similar number of pores available for capillary absorption as the other mixtures. Finally, T1 had a more matching behavior with similar values for capillary water absorption and volume of intruded mercury.

3.3 ACCELERATED DETERIORATION TESTING

3.3.1 Accelerated carbonation

Results for the carbonation depth are shown in Figure 8.

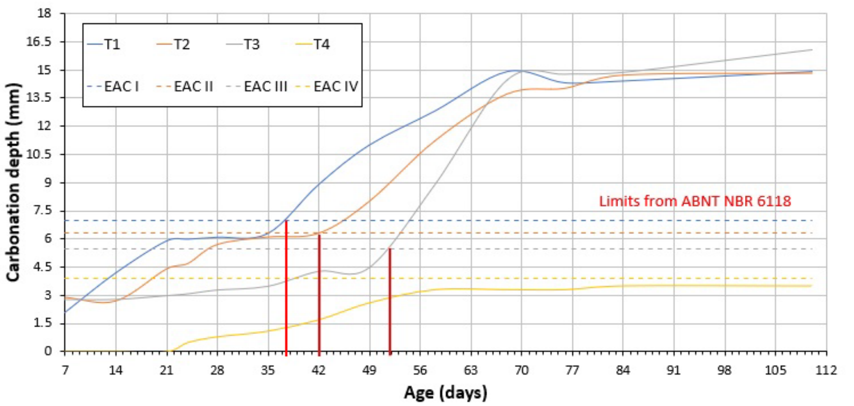

Figure 8. Carbonation depth values for the concrete mixtures of this study and EAC plateaus limits- dashed lines present the limits from ABNT NBR 6118.

Figure 8 shows that T4 presented a slow growth, with an eventual plateau between two ages and a maximum limit value of 3.5 mm. Mixture T3 also presented slow growth up to 35 days but a sharp increase between 36 and 58 days, during which the front grew from 3.5 mm to 8.94 mm for a 155% rise. The eventual maximum front for T3 was 16.13 mm. Mixture T2 had a gradual growth at each age and reached the predicted theoretical value at 49 days, while T1 had a maximum penetration of 14.88 mm. Results indicated that a depth of around 14 mm was likely a saturation point for CO_2 penetration due to the asymptotic behavior of T1, T2 and T3.

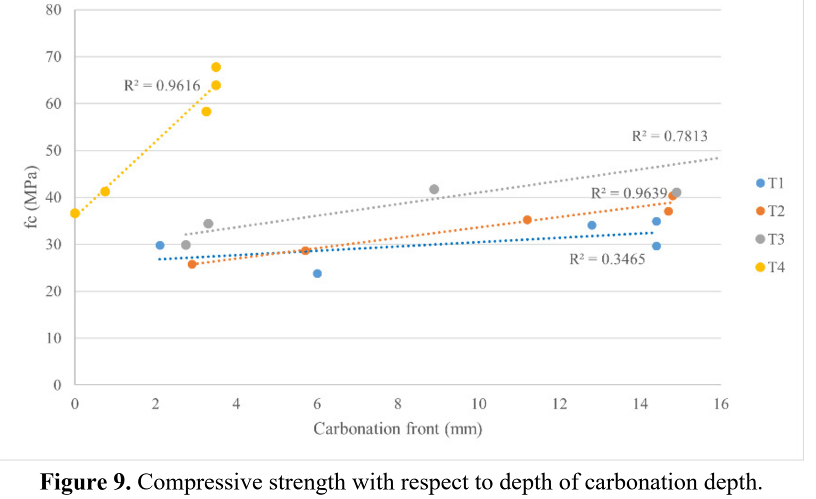

Figure 9. Compressive strength with respect to depth of carbonation depth.

Figure 9 presents compressive strength values concerning the carbonation depth for the approximate ages of this study. Results show a similar behavior for T1, T2, T3 and T4 of stagnation of the carbonation depth as compressive strength increased. However, the carbonation depth values of T4 remained below those of the other concrete mixtures. A linear behavior was observed for T2, T3 and T4 while variations in compressive strength reduced the correlation coefficient of T1 to 0.35. These results detach that, until T3, the differences in compressive strength conduce to smooth variations in carbonation front. Trace 4, however, stood out with low values, showing better performance against the carbonation attack.

Barin [36] reported that with higher values of compressive strength, the carbonation rate decreases. In this case, concrete was made from white cement and blast furnace slag with compressive strength between 45 MPa and 65 MPa. Kirchheim [37] evaluated concrete mixtures with 5 types of cement and obtained relationships between compressive resistance and carbonation depth with R^2 between 84.96% and 99.85%. It was also noted that despite strictly adhering to defined models, results were affected not only by total porosity and compressive strength (determinants in CO_2 penetration) but also pore structure and chemical composition of cements.

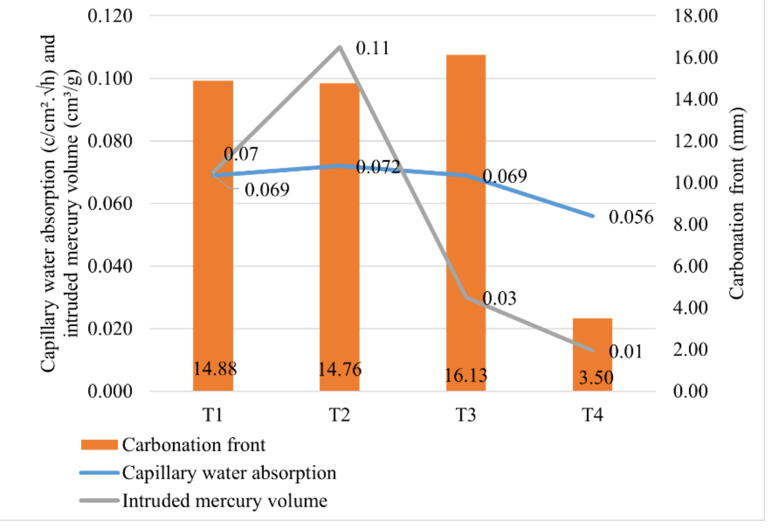

Figure 10. Comparison of capillary water absorption, intruded mercury volume and carbonation depth.

To examine the effect of void spaces and the distribution of capillary pores on concrete durability, Figure 10 compares water absorption and MIP with carbonation depth results. The behavior observed was consistent for all concrete mixtures except for the MIP of T2. Mixture T1 presented similar capillary water absorption values and mercury intrusion for a final carbonation depth of 14.88 mm. In contrast, T2 presented capillary water absorption similar to T1 but with much higher mercury intrusion while the final carbonation depth was slightly smaller at 14.76 mm, likely due to the variation in compressive strength. Mixture T3 presented lower intruded mercury volume, similar capillary water absorption but higher carbonation penetration than all the other concretes. There were some indicators of possible pore bridging (or saturation) stagnating CO_2 penetration at around 14 mm – a value close to the final penetration values for T1, T2 and T3. Mixture T4 presented the smallest carbonation penetration and capillary water absorption with CO_2 penetration decreasing 78.3% with respect to T3. Bao et al. [38] noted that capillary absorption had a great effect on concrete durability, even greater than the thickness of the transition zone. Overall, results showed that decreases in mercury intrusion also decreased the carbonation depth and, at a compressive strength of 40 MPa, there was an elevated decrease of CO_2 ingress in concrete.

3.3.2 Chloride attack (salt spray)

Chloride attack was evaluated at several ages for all concrete mixtures and the results are shown in Figure 11. Potential values were considered while outlier data points were discarded.

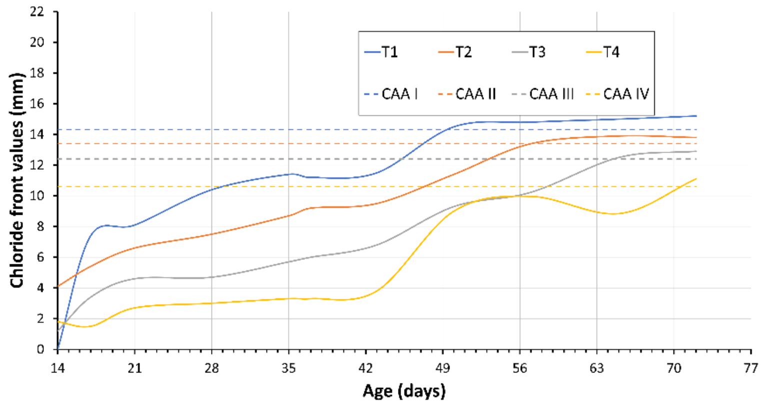

Figure 11. Chloride front values for the concrete mixtures of this study and EAC plateaus limits - Dashed lines present the limits from ABNT NBR 6118.

Initially, a solution of silver nitrate with a concentration of 0.5 mol was used but produced no results. Thus, it was necessary to increase the concentration to 1.0 mol to obtain the appropriate reaction. Figure 11 shows that T1 had an increasing chloride ion penetration up to the 7th data point, which decreased. The chloride ion penetration predicted from the theoretical Clear and Hay [18] model for T1 was reached at 50 days with the evolution up to this point having an R^2 of 0.95. A linear growth in chloride ion penetration was also observed for T2 with the theoretical prediction reached at 57 days and an R^2 of 0.98. The penetration fronts for T3 and T4 were reached at 65 days and 72 days, respectively. It should be noted that concrete specifications for environments with tides or salt spray (T3 for EAC III and T4 for EAC IV) had the most resistance to chloride ion penetration. Overall, the results for all concrete mixtures of this study were in agreement with theoretical model predictions and recommendations of standard ABNT NBR 6118 [7]. This presented an inversely proportional relation between chloride ion penetration depth and compressive strength as seen in Figure 11.

Figure 12 shows the relation between compressive strength and chloride penetration depth. All concrete mixtures demonstrated linear relations with higher compressive strength values corresponding to lower chloride ion penetration depths. A similar inverse proportionality between these variables was also reported by Verma et al. [39], however, with a low $R^2 = 0.226$ due to the outlier data points in some samples.

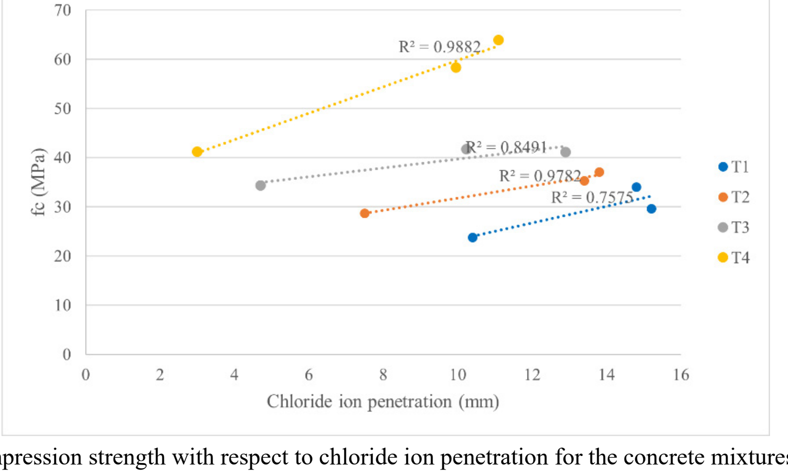

Figure 12. Compression strength with respect to chloride ion penetration for the concrete mixtures of this study.

Jang et al. [40] evaluated concretes with pozzolans and a few mixtures presented linear relationships as well. This stressed the need for further studies to properly assess the effect of different materials used in concrete composites. Cândido et al. [41] noted a pre-existing relation between pore alignment and both concrete strength and chloride ion attack. However, total porosity or void index might not be representative of the ingress of this agent since, as noted by Helene [13], the level of mass transport depended on pore diameter. Consequently, more could be glanced by evaluating the relation between capillary water absorption, intruded mercury volume and chloride ion penetration as shown in Figure 13.

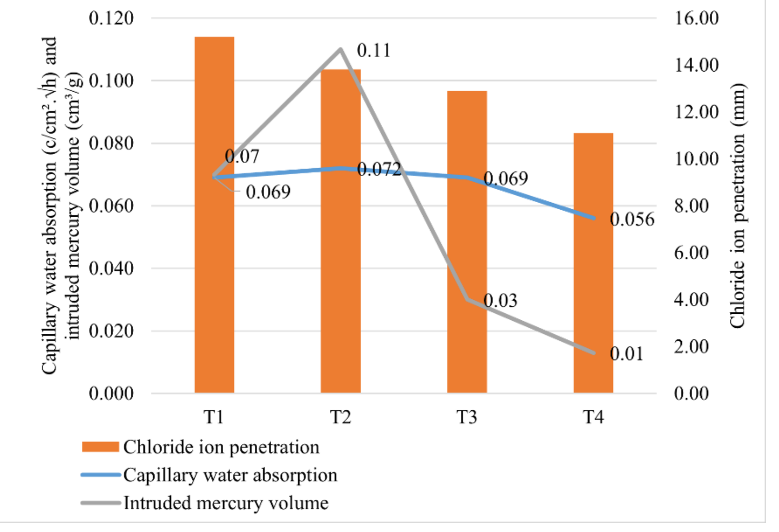

Figure 13. Comparison of capillary water absorption, intruded mercury volume and chloride ion penetration.

Figure 13 showed similar trends between capillary water absorption and chloride ion penetration, albeit with larger variations in the latter. Intruded mercury volume variations were also consistent with the other two variables despite the outlier point for T2. This agreed with Sato [42] which compared concrete pore diameter with chloride ion penetration load and obtained an R^2 of 0.9586. Hamada et al. [43] considered void space volume and distribution in the concrete used for the cover to estimate reinforcement corrosion, thus reinforcing the relation between these properties and the material's durability.

3.4 COVER FOR EACH EAC AND COMPRESSIVE STRENGTH

Table 6 shows a summary of carbonation depth and chloride ion penetration results with respect to the concrete mixture and EAC. From this, the necessary cover for each reinforcement was determined for each concrete class and EAC. It should be noted that the cover for EAC IV concerning CO_2 ingress was not obtained theoretically but from the end of testing at 110 days.

Table 6 – Nominal reinforcement cover (mm) from accelerated carbonation and chloride ion penetration with respect to concrete mixture and EAC class.

Concrete	Aggressive agent	EAC			
		I	II	III	IV
T1	CO_2	9	11	12.8	14.9
	Cl^-	14.5	14.8	15	15.2
T2	CO_2	6.3	8	11.2	14.8
	Cl^-	11.4	13.4	13.9	13.8
T3	CO_2	4.3	4.5	8.9	16.1
	Cl^-	9.3	10.2	12.5	12.9
T4	CO_2	1.7	2.6	3.3	3.5
	Cl^-	9	10	8.8	11.1

As shown in Table 6, the nominal cover values for almost all concrete mixtures were thicker for chloride ion penetration than carbonation (except for T2.III and T3IV). Consequently, it would be the more conservative estimates to be used. Moreover, the resistance to Cl- penetration was relatively similar across concrete mixtures at each EAC. This was not necessarily the same for carbonation, which had more significant variations across concrete mixtures and pointed at the possibility of estimating nominal cover with respect to fck. It could be considered for EAC I and II, which are more related to the presence of CO_2.

Vesikari [44] stated that the speed of carbonation was dependent on the permeability of concrete. Low permeability concretes, such as mixture T4 (confirmed from measurements of void index, porosimetry, and capillary water absorption in this study), had low carbonation rates. Crauss [45] noted that the speed of chloride ion attack was affected by the composition of concrete, environmental chloride concentration, and weather conditions. Thus, accelerated test conditions, such as in this study, resulted in a much faster process for all concrete composites.

Pauletti [46] pointed out that carbonic gas concentration becomes particularly influential in accelerated carbonation testing. Consequently, reduced concentrations were used to prevent distortions in the results. However, it should be noted that even if higher CO_2 had been used, surface pore bridging could have prevented penetration from reaching the expected front levels.

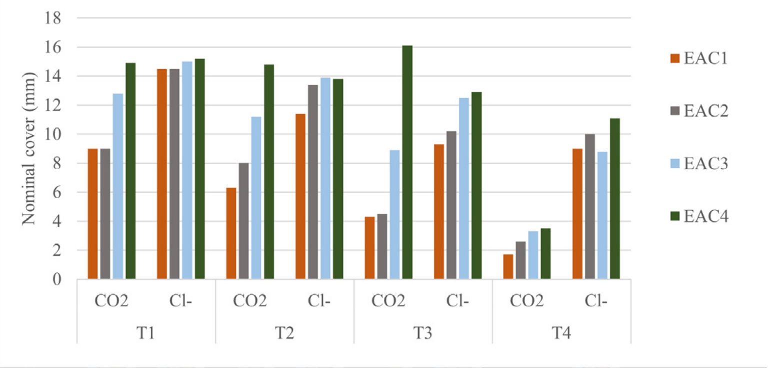

Figure 14. Nominal cover with respect to EAC grouped by concrete mixtures.

Figure 14 presents the nominal cover for each concrete mixture with respect to EAC grouped with respect to the concrete mixture. Mixture T1 had similar cover values for Cl- across all EAC and these values were presumed as the necessary covers. In contrast, CO2 front covers were similar between EAC I and II, and increasingly thicker covers were required for EAC III and IV. Mixture T2 also had similar values of cover for Cl- across all EAC classes, but a steep linear increase was shown with respect to EAC in response to the CO2 front. Cover values were significantly different for mixture T3 with a linear increase for Cl- across EAC, while cover in the CO2 front for EAC I and II were similar and much thinner than compared to T1 and T2. Mixture T4 required the least cover of all concretes, below 4 mm, with respect to CO2 front while Cl- penetration had no clear pattern but with the most cover required at EAC IV.

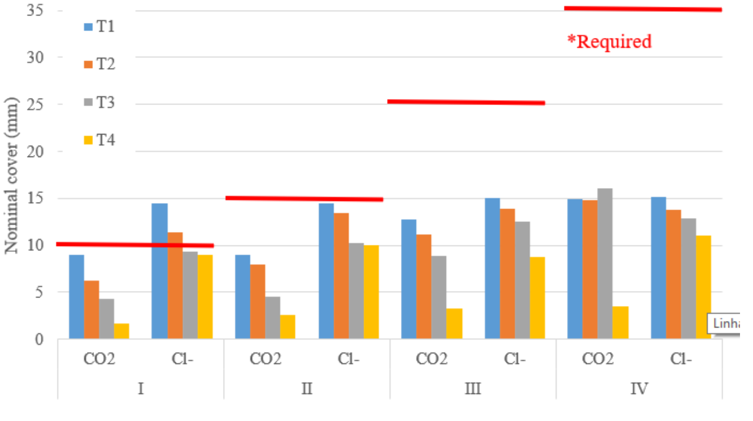

Figure 15 – Nominal cover with respect to concrete mixtures grouped by EAC.

Figure 15 presents nominal cover values with respect to concrete mixture grouped by EAC. The horizontal red lines represented the required covers for each EAC class in standard ABNT NBR 6118 [7]. As seen in the figure, nominal cover varied considerably with concrete mixtures, with the most cover being necessary for the mixtures with the least compressive strength. The most linear behavior was noted for chloride ion penetration and EAC IV while, unexpectedly, the thickest cover was required for mixture T3 under the CO_2 front. For each EAC, the thicker covers tended to be required for chloride ion penetration rather than the carbonation depth.

As mentioned before, the results presented a higher significance of compressive strength when considering trace 4, which showed a higher gap between the results obtained and the values required.

Table 7 – Comparison of nominal cover values from experiments and recommended by standards.

Concrete	Type of attack	EAC I: ABNT NBR 6118***	EAC I: Cover	EAC II: ABNT NBR 6118	EAC II: Cover	EAC III: ABNT NBR 6118	EAC III: Cover	EAC IV**: ABNT NBR 6118	EAC IV**: Cover
T1	CO_2	Slab:	9	Slab:	11	Slab:	12.8	Slab:	14.9
	Cl	10 mm	14.5	15 mm	14.8	25 mm	15	35 mm	15.2
T2	CO_2		6.3		8		11.2		14.8
	Cl	Beam/Column:	11.4	Beam/Column:	13.4	Beam/Column:	13.9	Beam/Column:	13.8
T3	CO_2	15 mm	4.3	20 mm	4.5	30 mm	8.9	40 mm	16.1
	Cl		9.3		10.2		12.5		12.9
T4	CO_2	Other*:	1.7	Other*:	2.6	Other*:	3.3	Other*:	3.5
	Cl	20 mm	9	20 mm	10	30 mm	8.8	50 mm	11.1

*"Other" are structural elements in contact with soil **Values for EAC IV were not predicted from theoretical models but from the carbonation depth of T4 at 110 days ***Values from standard ABNT NBR 6118 did not include their 10 mm tolerance margin.

Table 7 compares experimental nominal cover values based on theoretical models and requirements of standard ABNT NBR 6118 [7]. For EAC I, the standard-recommended nominal covers were similar to the results of T2, T3, and T4, with the requirements for T1 larger than prescribed in the standard for all mixtures. For EAC II, results from tests were below standard-recommended values, and a difference of 4.84 mm was noted between EAC I and EAC IV. This suggested that different cover values may be used in accordance with distinct concrete mixtures. The nominal cover values required in the standard were much larger than what was obtained from accelerated testing for EAC III and IV. To highlight the discrepancies, the maximum differences between these values were of 6.16 mm and 4.1 mm for T1 under EAC III and T4 under EAC IV, respectively. The variation in the required protection level of structures under different EAC was also evaluated by Mumberger et al. [47] and longer service life periods required corresponding adequate cover levels. The analysis format of the standard AS 3600 [9] is used in Table 8 to present a summary of the necessary reinforcement cover with respect to compressive strength across EACs.

Table 8 – Nominal cover with respect to compressive strength and EAC class.

EAC	Nominal cover (mm), Compressive strength (MPa): ≥ 20	≥ 25	≥ 30	≥ 40
I	14.5	11.4	9.3	9.0
II	14.8	13.4	10.2	10.0
III	15	13.9	12.5	8.8
IV	15.2	14.8	16.1	11.1

It should be noted that the cover values selected for each combination were the largest between chloride ion attack and carbonation depth. Table 8 shows that a decrease in nominal cover in concretes of higher strength could allow savings in cost, structural weight, cross section and other parameters. This However, these savings were beyond the scope of this study which focused instead on proving the viability of more than one class of concrete for each EAC. These results highlight the relevance of the mechanical resistance analyses of the mixes as an indication of how the behavior will be before the agents that promote the deterioration of the concrete.

Finally, Table 9 presents the nominal cover for the predominant aggression agent for each EAC: these were CO_2 exposure for EAC I and II and salt spray for EAC III and IV.

Table 9 – Nominal cover for predominant aggressive agent of each EAC.

EAC	Nominal cover (mm)			
	Compressive strength (MPa)			
	≥ 20	≥ 25	≥ 30	≥ 40
I	9	6.3	4.3	1.7
II	11	8	4.5	2.6
III	15	13.9	12.5	8.8
IV	15.2	13.8	12.9	11.1

Results denoted an increasing linear relation between nominal cover as EAC increased for concretes with a prescribed compression strength limit. For example, at EAC IV, concrete with a strength of 20 MPa would require a nominal cover 37% thicker than a concrete with strength of 40 MPa (recommended by standards). Another example would be at EAC II, if a 40 MPa strength concrete was to be used instead of 20 MPa (the minimum required by standards), the nominal cover would decrease by 67.5%.

The results of this study highlighted the variations in nominal cover when more leeway was considered in the compressive strength of the concrete mixture. In the case of Table 9, by focusing on the predominant aggressive agents, nominal cover decreased considerably for EAC I and II, which did not occur at EAC III and IV due to the severity of the chloride ion attack.

CONCLUSIONS

The following conclusions were drawn from the results of this study:

- In accelerated deterioration testing, concretes had distinct responses depending on the aggression agent. Samples exposed to chloride ion attack through salt spray presented rapid decay and reached predicted EAC levels in 72 days. The steep deterioration was linear for most concrete mixtures.
- Samples exposed to accelerated carbonation remained under testing for 110 days without reaching the carbonation depth predicted by the Hamada [16] model for EAC IV. This was likely due to impaired carbonic gas penetration due to decreased porosity such as in mixture T4.
- For most tests, nominal reinforcement cover was larger from chloride ion aggression when compared to carbonation depth. Results also confirmed the hypothesis that necessary cover for each EAC varied based on the type of concrete, its specified compressive strength, w/c ratio and cement usage.
- It should be noted that standard ABNT NBR 6118 [7] could have more flexible specifications for concrete and present more than one option of compressive strength concrete for each EAC. More specifically, this was clearly demonstrated in the possible decrease in nominal cover if a concrete with compressive strength of at least 30 MPa was used. However, this result did not consider faults and defects in the production of concrete.
- Considerable changes in nominal cover could arise if a concrete with a distinct strength different from specified in standards was to be used for a particular EAC. However, it was not the objective of this study to supply any recommendation of nominal cover since the scope with regards to materials and evaluated properties was not sufficiently broad.

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REFERENCES

[1] G. B. Wally, F. C. Magalhães, and L. C. P. Silva Fo., "From prescriptive to performance-based: an overview of international trends in specifying durable concretes," *J. Build. Eng.*, vol. 52, pp. 1–10, Nov. 2022, http://dx.doi.org/10.1016/j.jobe.2022.104359.

[2] I. Elkhaldi et al., "Towards global indicator of durability performance and carbon footprint of clinker-slag-limestone cement-based concrete exposed to carbonation," *J. Clean. Prod.*, vol. 380, no. Pt 1, pp. 1–15, Dec. 2022, http://dx.doi.org/10.1016/j.jclepro.2022.134876.

[3] J. Opon and M. Henry, "Implementation of a multicriteria analytical framework for the sustainability evaluation and comparison of concrete materials considering methodological uncertainties," *J. Clean. Prod.*, vol. 344, no. 131057, pp. 1–13, Feb. 2022, http://dx.doi.org/10.1016/j.jclepro.2022.131057.

[4] G. De Schutter, "No concrete is sustainable without being durable!," in *Proc. XIII Int. Conf. Durability Build. Mater. Compon.*, São Paulo, 2014, pp. 38–44.

[5] S. Yuvaraj et al., "Influence of corrosion inhibitors in reinforced concrete – a state of art of review," *Mater. Today Proc.*, vol. 68, pp. 2406–2412, Sep. 2022, http://dx.doi.org/10.1016/j.matpr.2022.09.118.

[6] K. Tuutti, *Corrosion of Steel in Concrete*. Stockholm: Cement Concr. Res. Inst., 1982.

[7] Associação Brasileira de Normas Técnicas, *Projeto de Estruturas de Concreto – Procedimento*, NBR 6118, 2014.

[8] Associação Brasileira de Normas Técnicas, *Concreto de Cimento Portland – Preparo, Controle, Recebimento e Aceitação – Procedimento*, NBR 12655, 2015.

[9] Australian Standard, *Concrete Structures*, AS 3600, 2009.

[10] Bureau of Indian Standards, *Plain and Reinforced Concrete – Code of Practice*, IS 456, 2000.

[11] European Committee for Standardization, *Concrete – Specification, Performance, Production and Conformity*, EN 206-1, 2013.

[12] American Concrete Institute, *Guide to Durable Concrete*, ACI 201.2R-08, 2008.

[13] P. Helene, "Contribuição ao estudo da corrosão em armaduras de concreto armado," Ph.D. dissertation, Univ. São Paulo, São Paulo, 1993.

[14] European Committee for Standardization, *Eurocode 2: Design of Concrete Structures - Part 1-2: General Rules - Structural Fire Design*, EN 1992-1-2, 2004.

[15] A. M. Neville, *Propriedades do Concreto*, 5ª ed. Porto Alegre: Bookman, 2015.

[16] M. Hamada, "Neutralization (carbonation) of concrete and corrosion of reinforcing steel," in *Proc. Int. Symp. Chemistry Cement*, Tokyo, 1969 pp. 343–369.

[17] F. Pacheco, "Investigação da relação entre os parâmetros de projeto das estruturas de concreto armado visando à durabilidade," Master thesis, Progr. Pós-Grad. Eng. Civil, Univ. Vale do Rio dos Sinos, São Leopoldo, 2016.

[18] K. C. Clear and R. E. Hay, *Time-To-Corrosion of Reinforcing Steel Slabs, vol. 1, Effect of Mix Design and Construction Parameters. Interim Report n° FWDA-RD-73-32*. Washington, D.C., USA: Fed. Highway Admin, 1973.

[19] C. Bob, "Probabilistic assessment of reinforced corrosion in existing structures," in *Proc. Int. Conf. Concr. Repair Rehabil*, Dundee, 1996. pp. 17–28.

[20] Associação Brasileira de Normas Técnicas, *Concreto para Fins Estruturais – Classificação pela Massa Específica, por Grupos de Resistência e Consistência*, NBR 8953, 2015.

[21] American Society for Testing and Materials, *Standard Practice for Operating Salt Spray (Fog) Apparatus*, ASTM B117, 2011.

[22] Associação Brasileira de Normas Técnicas, *Concreto – Determinação da Consistência pelo Abatimento do Tronco de Cone*, NBR 16889, 2020.

[23] Associação Brasileira de Normas Técnicas, *Concreto – Ensaios de Compressão de Corpos-de-Prova Cilíndricos*, NBR 5739, 2007.

[24] Associação Brasileira de Normas Técnicas, *Argamassa e Concreto Endurecidos – Determinação da Absorção de Água, Índice de Vazios e Massa Específica*, NBR 9778, 2009.

[25] RILEM TC 116 PCD, "Permeability of concrete as a criterion of its durability. Concrete durability – an approach towards performance testing," *Mater. Struct.*, vol. 32, no. 4, pp. 174–179, 1999.

[26] R. Polder, "RILEM TC 154 EMC. Electrochemical techniques for measuring metallic corrosion. Test methods for on site measurement of resistivity of concrete," *Mater. Struct.*, vol. 33, pp. 603–611, 2000.

[27] C. Z. Rissardi, C. F. N. Souza, F. Pacheco, R. Christ, and L. F. Silveira, "Chloride attack evaluation on concrete compositions according to Brazilian standard ABNT NBR 6118 specification," *J. Build. Pathol. Rehabil.*, vol. 1, pp. 1–19, Dec. 2016, http://dx.doi.org/10.1007/s41024-016-0004-7.

[28] J. J. O. Andrade and B. F. Tutikian, "Resistência mecânica do concreto," in *Concreto: Ciência e Tecnologia*, B. Tutikian, F. Pacheco, G. Isaía, and I. Battagin, Eds., São Paulo: IBRACON, 2022, vol. 1, pp. 699–738.

[29] X. Chen, S. Wu, and W. Zhou, "Influence of porosity on compressive and tensile strength of cement mortar," *Constr. Build. Mater.*, vol. 40, pp. 869–874, Mar. 2013, http://dx.doi.org/10.1016/j.conbuildmat.2012.11.072.

[30] A. K. Yasin, R. Bayuaji, and T. E. Susanto "A review in high early strength concrete and local materials potential," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 267, pp. 012004, Nov. 2017, http://dx.doi.org/10.1088/1757-899X/267/1/012004.

[31] R. A. Medeiros-Junior, G. S., Munhoz, and M. H. F. Medeiros, "Correlations between water absorption, electrical resistivity and compressive strength of concrete with different contents of pozzolan," *Rev. ALCONPAT*, vol. 9, no. 2, pp. 152–166, May 2019, http://dx.doi.org/10.21041/ra.v9i2.335.

[32] G. Isaia, “A água no concreto,” in *Concreto: Ciência e Tecnologia*, B. Tutikian, F. Pacheco, G. Isaía, and I. Battagin, Eds., São Paulo: IBRACON, 2022, vol. 1, pp. 371–410.

[33] S. P. Zhang and L. Zong, “Evaluation of relationship between water absorption and durability of concrete materials,” *Adv. Mater. Sci. Eng.*, vol. 2014, pp. 650373, Apr. 2014, http://dx.doi.org/10.1155/2014/650373.

[34] N. Bozkurt and S. Yazicioglu, “Strength and capillary water absorption of lightweight concrete under different curing conditions,” *Indian J. Eng. Mater. Sci.*, vol. 17, pp. 145–151, Apr. 2010.

[35] P. K. Mehta and P. J. M. Monteiro, *Concreto: Microestrutura, Propriedades e Materiais*, 2ª ed. São Paulo: IBRACON, 2014.

[36] D. S. Barin, “Carbonatação e absorção capilar em concretos de cimento Portland branco com altos teores de adição de escória de alto forno e ativador químico,” Master thesis, Prog. Pós-Grad. Eng. Civil, Univ. Fed. Santa Maria, Santa Maria, 2008.

[37] A. P. Kirchheim, “Concreto de cimento Portland branco estrutural: avaliação da carbonatação e absorção capilar,” Master thesis, Prog. Pós- Grad. Eng. Civil, Esc. Eng., Univ. Fed. Rio Grande do Sul, Porto Alegre, 2003.

[38] H. Bao et al., “Evolution of ITZ and its effect on the carbonation depth of concrete under supercritical CO_2 condition,” *Cement Concr. Compos.*, vol. 126, pp. 1–16, Feb. 2022, http://dx.doi.org/10.1016/j.cemconcomp.2021.104336.

[39] S. K. Verma, S. S. Bhadauria, and S. Akhtar, “Evaluating effect of chloride attack and concrete cover on the probability of corrosion,” *Front. Struct. Civ. Eng.*, vol. 7, no. 4, pp. 379–390, Dec. 2013, http://dx.doi.org/10.1007/s11709-013-0223-9.

[40] J. G. Jang et al., “Resistance of coal bottom ash mortar against the coupled deterioration of carbonation and chloride penetration,” *Mater. Des.*, vol. 93, pp. 160–167, Mar. 2016, http://dx.doi.org/10.1016/j.matdes.2015.12.074.

[41] T. G. Cândido et al., “Mechanical performance and chloride penetration resistance of concretes with low cement contents,” *Rev. IBRACON Estrut. Mater.*, vol. 15, no. 6, pp. 1–14, Oct. 2022, https://doi.org/10.1590/S1983-41952022000600008.

[42] N. M. N. Sato, “Análise da porosidade e das propriedades de transporte de massa de concreto com vistas à avaliação de suas durabilidades,” Doctoral dissertation, Esc. Polit., Univ. São Paulo, São Paulo, 1998.

[43] H. Hamada et al., “Experimental study on relationship between void under reinforcing bar and its corrosion,” *Cement Concr. Res.*, vol. 63, no. 1, pp. 428–433, Jan. 2009, http://dx.doi.org/10.14250/cement.63.428.

[44] E. Vesikari, *Carbonation and Chloride Penetration in Concrete with Special Objective of Service Life Modelling by the Factor Approach. Research Report VTTR0477109*. Espoo, Finland: Tech. Res. Cent. Finland, 2009.

[45] C. Crauss, “Penetração de cloretos em concretos com diferentes tipos de cimento submetidos a tratamento superficial,” Master thesis, Prog. Pós-Grad. Eng. Civil, Univ. Fed. Santa Maria, Santa Maria, 2010.

[46] C. Pauletti, “Análise comparativa de procedimentos para ensaios acelerados de carbonatação,” Master thesis, Prog. Pós-Grad. Eng. Civil, Esc. Eng., Univ. Fed. Rio Grande do Sul, Porto Alegre, 2004.

[47] F. B. Mumberger, B. F. Tutikian, and F. L. Bolina, “Proposed durability parameters for reinforced concrete structures with design service life between 50 years and 100 years in Brazil,” *Rev. IBRACON Estrut. Mater.*, vol. 15, no. 6, pp. 1–19, Sep. 2022, http://dx.doi.org/10.1590/S1983-41952022000600003.

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