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**Technical Paper**

# Effect of pre-loading on chloride diffusion in concrete

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**Abstract:** This study concerns experimental works to examine the effect of pre-compressive stress on chloride diffusivity in concrete. Three types of concrete (C1, C2, C3) with different compressive strengths were examined in two environmental conditions (spray zone and atmospheric zone). Four different stress levels (0%, 30%, 50%, and 80 % of the stress at ultimate load) were applied to 100 mm diameter concrete specimens. After loading and subsequent, specimens were treated and put into chloride diffusivity cell of rapid chloride permeability test based on the ASTM C1202 test. Chloride diffusion coefficient of concretes was calculated from those results considering the effect of pre-compressive stress. The experimental results show that the chloride permeability increased with the increase in pre-compressive stress. A correlation between the relative diffusion coefficient of pre-compressive to non-load ($D\sigma/D_0$) and the pre-compressive stress levels for each of the concrete type was obtained in this experiment. Finally, these values were used for predicting the corrosion initiation of rebar in reinforced concrete structures.

**Keywords**: concrete, pre-compressed stress, chloride, load, service life, reinforced concrete.

## 1. Introduction

Durability indicators of concrete such as permeability and diffusion are the main transport properties for concrete because they control the ingress of water, oxygen, carbon dioxide, and chlorides which cause the electro-chemical reaction of corrosion of rebar. Studies have been carried out since the past decades to understand the service life of reinforced concrete structures [1,2]. However, the disadvantage of these models is that most conclusions were made considering a perfect and undamaged concrete, without applying stress and modeling the possible cracks.

In practice, the prediction of the service life of new or existing concrete structures in the marine environment is a global challenge since the concrete structures not only handle loading but also are exposed to various environmental conditions. Therefore, it is more realistic to study the deterioration mechanism of a concrete structure under the combined effects of mechanical loading and environmental factors [3-7].

Zhiming et al. showed that chloride permeability increases in ultra-high-performance concrete (UHPC) after suffering tensile and compressive loadings [8]. Wang et al. showed that concrete with service loading of over 50% of the stress at ultimate load can have 2 to 4 times higher chloride migration coefficients compared to non-loaded concrete [9]. Depending on the level of loads, the concrete can be subjected to microstructure changes, leading to damage (micro-cracks and macro-cracks), which can affect the chloride penetration process. In the actual structures (bridge, floor, etc.) the load acting on the structure will cause "residual effect" in the concrete, resulting in damaging the concrete. This is a non-reversible process and the residual effect of the load will increase the risk of chloride penetration.

This research concerns the prediction of the corrosion initiation of rebar in reinforced concrete structures (RCS) based on the comparison of chloride concentration at rebar surface and the critical value, considering the effect of pre-compressive stress in concrete. A hydro-mechanic relationship was proposed for the acceleration of chloride diffusivity coefficient with pre-compressive relative stress in concrete; this law was then introduced in

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corrosion initiation model based on the second Fick's law and applied for predicting the service life of RCS. Two different types of concrete are examined experimentally: normal concrete (NC) and high performance concrete (HPC). Two exposure conditions of the marine environment, including the spray zone and the atmospheric zone, were also examined in this research.

## 2. Experimental program

### 2.1 Materials and composition of mixtures

Portland cement, silica fume, and fly ash were used to prepare plain and blended cement concrete mixtures. Silica fume 8 % and fly ash 20 % were used to replace Portland cement by mass. Crushed limestone was used as the coarse aggregate while dune sand was used as the fine aggregate. The aggregate grading conformed to ASTM C33 limits [10]. The specific gravity and water absorption of the coarse aggregate were 2.92 and 0.86%, respectively. For fine aggregates, these values were 2.64 and 0.8%, respectively.

The concrete mix was designed in accordance with ACI 211.1 [11] and ACI 211.4 [12]. The compositions of the concrete are shown respectively in Table 1.

Table 1 – The composition of mixtures for 1 $m^3$ of concrete

| Materials | Concrete types | | |
|---|---|---|---|
| | C1 | C2 | C3 |
| Cement, kg | 385 | 408 | 430 |
| Silica fume, kg | --- | --- | 47 |
| Fly ash, kg | --- | 82 | 117 |
| Sand, kg | 605 | 775 | 610 |
| Coarse aggregate, kg | 1135 | 1135 | 1097 |
| Water, kg | 175 | 172 | 170 |
| Superplasticizer, litre | --- | 6.7 | 7.85 |
| Dry density, kg/$m^3$ | 2300 | 2445 | 2471 |
| Water/binder (*w/b*) | 0.45 | 0.35 | 0.29 |
| Compressive strength, MPa | 38 | 57 | 75 |

Table 2 – Experimental results of chloride ion permeability for concretes

| Pre-compressive stress level | Rapid chloride permeability - *RCP* (coulombs) | | | | | |
|---|---|---|---|---|---|---|
| $\sigma/\sigma_{max}$ | C1 | | C2 | | C3 | |
| 0 | 2893 | 2719 | 537 | 576 | 211 | 257 |
| | 2643 | | 616 | | 270 | |
| | 2620 | | 576 | | 291 | |
| 0.3 | 3520 | 3373 | 634 | 621 | 251 | 321 |
| | 3316 | | 646 | | 335 | |
| | 3284 | | 583 | | 377 | |
| 0.5 | 3702 | 3592 | 678 | 645 | 284 | 366 |
| | 3647 | | 625 | | 394 | |
| | 3426 | | 633 | | 421 | |
| 0.8 | 3825 | 4045 | 753 | 713 | 298 | 377 |
| | 3910 | | 672 | | 402 | |
| | 4400 | | 714 | | 432 | |

### 2.2 Choride ion penetration test in stressed concrete

Chloride ion permeability was determined for all concrete mixtures in this study using ASTM C1202 test method, also called Rapid Chloride Permeability Testing (RCPT) [13]. In the RCPT, specimens were placed between two acrylic cells. One of the cells was filled with a 0.3 mole/L NaOH solution and the other cell was filled with a 3% NaCl solution. The cells were connected to a 60-V power source. The current (in milliamps) was measured and recorded during a 6 hours period, and the total charge which passed through the specimen was computed by integrating the current and time.

Curing period of concrete specimens was 28 days in a water-curing tank placed in a temperature room, then in a moist room for a week (100% relative humidity and 20$^o$C). After that, the specimens were divided into 4 groups. The groups are pre-compressed with the relative stress levels in the concrete as $\sigma/\sigma_{max}$ = 0; 0.3; 0.5; 0.8 and then unloaded. The concrete specimens were tested under an axial compressive loading condition to reach the predetermined load levels corresponding to expected stress. Each load level was sustained for varying periods up to 2h, then unloaded. After unloading, concrete discs of 50 mm in thickness were cut off from the central portion of the cylindrical specimens; these discs were sealed with two epoxy resin coats in order to ensure one dimensional chloride flow through the discs. The chloride ion permeability test sample size was 50 mm x 100 mm (height x diameter).

### 2.3 Results and discussion

The experimental results of rapid chloride ion permeability (RCPT test) for 3 concrete types (C1, C2, C3) corresponding to the pre-compression stress values in concrete are shown in Table 2.

By comparison of the three concrete samples, concrete C3 (20% fly ash and 8% silica fume) showed lower coulombs value after 28 days of curing period. Chloride permeability of concrete C1 is "moderate" and chloride permeability of concrete C2 and C3 is “very low”. This difference can be explained by the microstructural change of concrete. Permeability of concrete depends mainly on the permeability of pastes which, in turn, depends on porosity and pore size distribution [14]. When Silica, containing fly ash and silica fume, is added to concrete, the pozzolanic reaction occurs between the silica glass ($SiO_2$) and the calcium hydroxide $Ca(OH)_2$. The hydration products produced fill the open capillary pores and improve the pore structure, changing the total porosity and pore size distribution [15]. Addition of pozzolans increased the total pore volume, however the pore size distribution was shifted toward finer pores and therefore the permeability of the concrete was reduced [16,17]. In addition, the decrease in water to cementitious materials ratio also causes a reduction of porosity which resulted in the increase in density of the concrete [17,18]. Hence, concrete containing fly ash and silica fume with a lower *w/b* ratio (C2, C3) shows lower permeability compared to normal concrete (C1). This is in line with the results of research on chloride permeability of other authors [5,19-21].

The results show variation of chloride permeability when changing the pre-compressive stresses for concrete C1, C2 and C3. This can be explained by the degradations caused by compressive loads, leading to changes in chloride permeability. The higher the load, the more damage risk there is in concrete, so the chloride ion permeability increases with increasing pre-compression stress in the concrete. However, the growth rate of the concrete types is different. Increasing chloride permeability of concrete C1 is greatest when the pre-compression stress increases. Yet, the permeability of concrete C2 and C3 increases more slowly.

A correlation between the chloride diffusion coefficient and chloride permeability of normal concrete (NC) and high-performance concrete (HPC) were reported by Stanish et al [3] and Olek et al [22]. Equations linking the effective chloride diffusion coefficient with resistivity and permeability of concrete such as:

$$D = 0.0088\,(RCP)^{0.76}\ (10^{-12}\ \mathrm{m^2/s}) \quad \text{for NC} \qquad (1)$$

$$D = 0.002\,RCP + 0.4\ (10^{-12}\ \mathrm{m^2/s}) \quad \text{for HPC} \qquad (2)$$

The equations are used to calculate the chloride diffusion coefficient $D$ of concrete types. The results are shown in Table 3.

Table 3 – Coefficient of chloride diffusion

| Pre-compressive stress level $\sigma/\sigma_{max}$ | Chloride diffusion coefficient, $10^{-12}$ m$^2$/s | | | | | |
|---|---|---|---|---|---|---|
| | Concrete C1 | | Concrete C2 | | Concrete C3 | |
| | $D$ | $D_\sigma/D_0$ | $D$ | $D_\sigma/D_0$ | $D$ | $D_\sigma/D_0$ |
| 0 | 3.59 | 1 | 1.55 | 1 | 0.91 | 1 |
| 0.3 | 4.22 | 1.17 | 1.64 | 1.06 | 1.04 | 1.14 |
| 0.5 | 4.43 | 1.24 | 1.69 | 1.09 | 1.13 | 1.24 |
| 0.8 | 4.85 | 1.35 | 1.83 | 1.17 | 1.15 | 1.26 |

Correlation between the chloride diffusion coefficient and pre-compressive stress in concrete are shown in Table 3 and Fig. 1. In the case of normal concrete C1, when the pre-compressive stress was $0.8\sigma_{max}$ (80% of ultimate compressive stress), the coefficient of chloride diffusion is greater than the one corresponding to non-loaded concrete, with a multiplier factor of 1.35. For high performance concrete (C2, C3), the factor is 1.17 and 1.26. The results show that the value $D_\sigma / D_0$ tended to increase slightly for high performance concrete (C2, C3) and increase quickly for normal concrete (C1) when increasing pre-compressive stress level. [23] It also shows that, for pre-compressive concrete, the chloride diffusion coefficient increases with the increase of porosity due to applied load. Additionally, when pre-compressive loads are applied, cracks appear and spread in concrete. So pre-compressive in concrete, and therefore the creation of micro or macro-cracks, leads to an increase of their transport properties because of higher porosity [9]. Cracks accelerate the diffusion of ion chloride, leading to damage and durability problems.

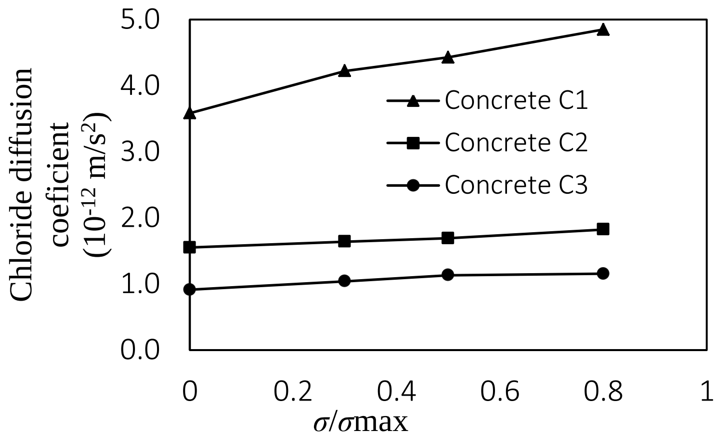



Fig 1 – Increased chloride diffusion coefficient according to the pre-compressive stress in concretes

## 3. Evaluation of rebar corrosion initiation in reinforced concrete structures considering the pre-compressive stress

The high corrosion rates generally detected in marine environment, the difficulty of modelling this mechanism and its effect on the structures led to the usual consideration of service life as the initiation period. The model for service life evaluation of concrete structures was developed from the equation calculating the concentration of chloride on rebar surface based on Fick's second law [4]:

$$C_x = C_s\left(1 - erf\left(\frac{x}{2\sqrt{Dt}}\right)\right) \quad (3)$$

Here, $C_x$ is the chloride concentration at depth $x$ of the concrete cover (% of concrete weight); $C_s$ is the chloride concentration on the surface (% of concrete weight); $D$ is the coefficient of chloride diffusion of concrete ($10^{-12}$ m$^2$/s); t is the considered time (years) and *erf* is the error function.

The corrosion process of rebar starts when $C_x = C_{cr}$ (the threshold required to initiate corrosion - % of concrete weight) at this moment, $x = h$ (concrete cover thickness, depth), and equation (3) can be rewritten as:

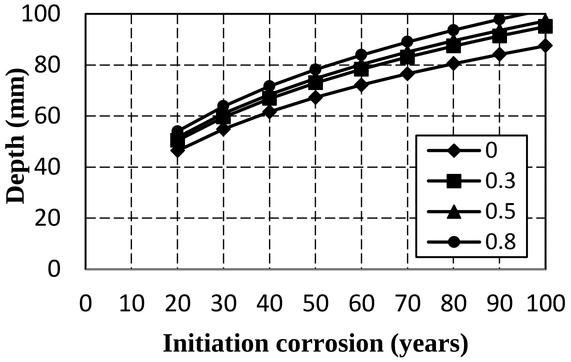
$$C_{cr} = C_s\left(1 - erf\left(\frac{h}{2\sqrt{Dt}}\right)\right) \quad (4)$$

Variation of the surface chloride concentration $C_s$ can be written following the formula proposed by Costa et al [21,24]:

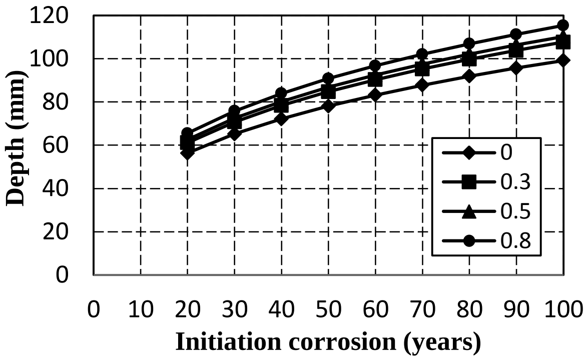
$$C_s = C_{so} \,.\, t^n \quad (5)$$

Here, $C_{so}$ is the surface chloride concentration after the first year, and $n$ is an empirical coefficient depending on the environmental conditions. (The values of $C_{so}$: % of concrete weight). In the spray zone, $C_{so} = 0.291$ and $n = 0.426$, in the atmospheric zone, $C_{so} = 0.128$ and $n = 0.476$ from the Danang (Vietnam) coastal area [25].

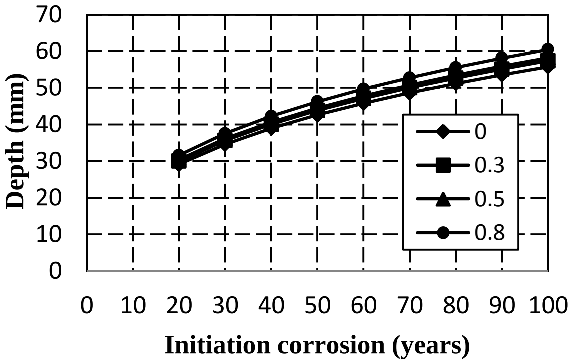
The values of $C_{cr}$ depend on various parameters (composition of concrete, type of cement, cover, exposure condition, etc.) and shall be established for each situation. A reference value generally assumed in Europe is 0.4% by weight of cement [24]. Considering this value and the studied concrete mixes, the value of $C_{cr}$ referring to the weight of concrete for mixes types C1, C2, and C3 is 0.07%, 0.08%, and 0.09%, respectively. Model to predict the coefficient of diffusion at a given age is, according to Mangat et al [26]:



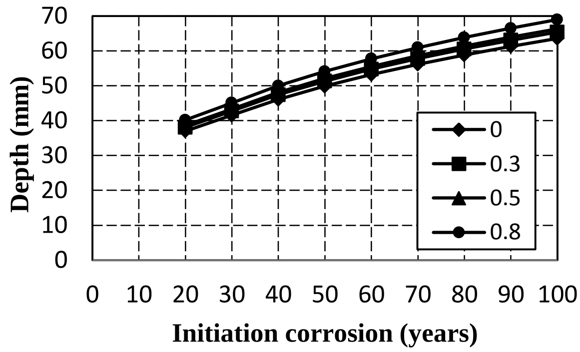

Concrete C1 – Atmosphere zone



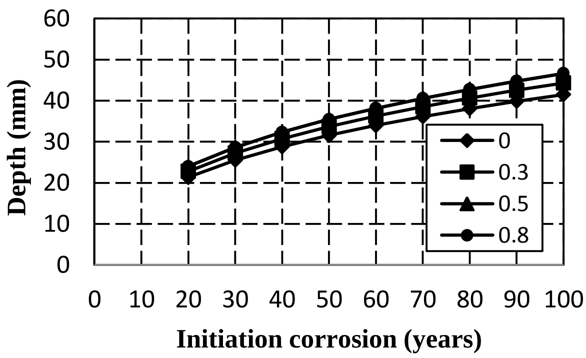

Concrete C1 – Spray zone



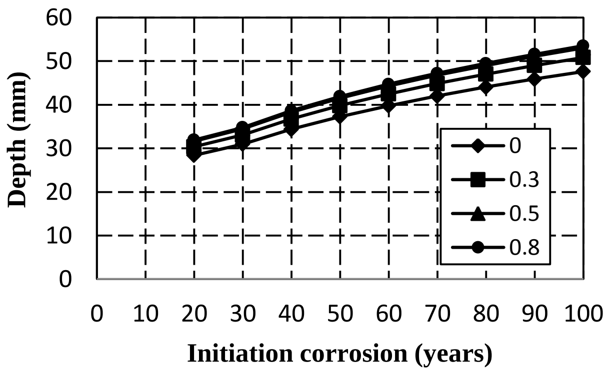

Concrete C2 – Atmosphere zone




Concrete C2 – Spray zone




Concrete C3 – Atmosphere zone




Concrete C3 – Spray zone

Fig. 2 – Time evolution of the critical chloride penetration for the various concretes and exposure conditions

Table 4 – Minimum concrete covers for the initiation of corrosion after 50 years

| Exposure condition | Concrete type | Minimum cover (mm) |
|---|---|---|
| Atmospheric zone | C1 | 67.2 |
| | C2 | 42.6 |
| | C3 | 31.6 |
| Spray zone | C1 | 78.1 |
| | C2 | 49.9 |
| | C3 | 37.3 |

$$D = D_{28}\left(\frac{t_o}{t}\right)^m \tag{6}$$

Where, $D_{28}$ = reference chloride diffusion coefficient at 28 days ($10^{-12}$ m²/s), $t_0$ = reference period ($t_0$ = 28 days = 0.767 year), $m$ = age coefficient ($m$ = 0.48).

The equation can thus be used to estimate the long-term penetration of the critical chloride content and allows to assess the service life.

$$h = 2\sqrt{D_{28}t_o^m \mathrm{t}^{1-m}}.erf^{-1}\left(1-\frac{C_{cr}}{C_{so}t^{\mathrm{n}}}\right) \tag{7}$$

The dependence of the service life on the cover thickness h considering the pre-compressive stress level was presented in the Fig. 2. When concrete is not loaded, the evolution of service life is similar to the results of Costa et al [21], [24]. The pre-compressive stress in concrete cover has significant impacts on the service life of RCS; indeed, with the same concrete cover thickness, the service life of RCS reduces rapidly when stress level increases. Accordingly, to achieve the desired durability, the concrete cover thickness should be increased when stress level increases.

This study shows that it is necessary to differentiate the various exposure conditions in marine environment as well as the concrete cover and mix composition requirements. Fig. 2 shows that a cover of 40 mm is not enough to guarantee a service life of 50 years, except for atmospheric exposure conditions and for good concrete quality. For normal concrete (C1) to ensure a service life of 50 years, the concrete cover thickness should be 67 mm in the atmospheric zone and 78 mm in the spray zone. The results of this study will help to establish the requirements which ensure an adequate durability of reinforced concrete structures in marine environment. In general, those requirements refer to the concrete mix composition and to the minimum cover.

The service life of RCS in the spray zone is significantly lower than in atmospheric zone with the same cover thickness and pre-compressive stress level. In the spray zone, with a concrete cover depth of 70 mm, the service life is reduced from 38 to 22 years when the pre-compressive increases from 0 to 0.8 maximum stress. In the atmospheric zone, with 70 mm depth of concrete cover, the service is reduced from 57 to 39 years when the pre-compressive increases from 0 to 0.8 maximum stress.

## 4. Conclusion

From the above results and discussions, it can be concluded that:

(1) Replacements of Portland cement by pozzolan (fly ash and silica fume) increases the resistance of concrete to chloride ingress and reduces its permeability. This study has shown that the chloride permeability of concrete using the pozzolans diminished markedly with a reduction of *w/b* ratio and tended to a very low value.

(2) The pre-compressive level of concrete can be obtained using an axial compression test, up to 80% of ultimate compressive strength. Compressive stresses in concrete increase the ingress of chloride; concrete C1 shows higher values. This can be explained by the permeability through the pores and the existence of micro-cracks and their evolution according to the applied load.

(3) Results show that there is a linear variation between the relative diffusion coefficient of pre-compressive to non-load (ratio $D_\sigma/D_0$) and the pre-compressive stress levels for each of concrete type. It can be used to evaluate the permeability behavior of concrete after suffering compressive loading.

(4) The service life of RCS in the marine environmental conditions were evaluated by using a proposed model considering the pre-compressive stress level of concrete. The results clarified significant influences of pre-compressive stress level in concrete on the service life of RCS. The recommended value of concrete cover depth of 100 mm for reinforced concrete structures in marine zones should be reconsidered in design and construction process if the risk of concrete damage is real.

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