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Water/Cement Ratio Randomness Effect on Reinforced Concrete Carbonation

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Abstract—The aim of this paper is the evaluation of carbonation depth, and the carbonation time which is the time necessary so that the face of carbonation arrives until the reinforcement from a probabilistic analysis, focusing specifically on the study of the randomness effect of the Water /Cement ratio on the reinforced concrete carbonation. Monte Carlo simulations are realized under the assumption that the Water /Cement ratio is random variable with a log-normal probability distribution.

Keywords—Water /Cement ratio, carbonation depth, carbonation time, lognormal random variable, carbonic gas CO_2, relative humidity

I. INTRODUCTION

The natural aging of concrete is accompanied with carbonation more or less important. This well known phenomenon originates from the small amount of carbon dioxide in the air, which is average of 0.03%. [1].

The degradations induced by the external conditions are ordered by defining several classes of exposure for the corrosion risk, depending on the environmental actions and concrete work conditions.

Minimal concrete covers requirements are associated with these classes. Among these classes, there is that corresponding to the corrosion induced by carbonation (Xc), which applies to the reinforced concrete exposed to the air and moisture.

Van Balen and Van Gemert have proposed deterministic mathematical models of carbonation, based on the mathematical formulation of carbonation and taking into account the effects of water content;

These deterministic models consider the action of Water /Cement ratio on the concrete compounds comprise some limits related to the random variation of the input model parameters, and the precise knowledge of these parameters requires a probabilistic approach enable to modeling the uncertainties and analyzing their dispersion effect[1,2].

In this paper, a probabilistic formulation is applied to carbonation phenomenon, and statistics integrates the influence of variation coefficient of water to cement ratio (W/C). Monte Carlo simulations are realized under the assumption that the Water /Cement ratio is random variable with a log-normal probability distribution.

II. CARBONATION MODELS

Physio-chemical aggressions of reinforced concrete structures, which are mainly of diffusion nature, are caused by external exposure.The aggressive agents propagate in the concrete by porosity, in the presence of carbonic gas and chloride ions.

Carbonation phenomenon is due to the calcium carbonate formation by reaction between cements and atmospheric carbon dioxide CO_2, this reaction arises as follows [3]:

$$CO_2+(OH)_2 \rightarrow H_2O+\text{alkaline bases} \rightarrow CaCO_3+H_2O \quad (1)$$

Several authors have proposed deterministic mathematical models of carbonation:

Papadakis and al consider the diffusion of CO_2 into the porous network and its dissolution in the interstitial liquid phase.

Saetta and al model is based on the coupled effects of moisture, heat and carbonation process.

The model of Al Akchar takes into account CO_2 diffusion and reaction on the Portland coupled to the drying of the material[4].

The Duracrat model results from the resolution of the diffusion equation of CO_2 in porosity of the concrete at constant temperature, the transfer of moisture is not considered but its influence is explicit [5].

All these deterministic models consider the action of carbon dioxide on the concrete compounds comprise some limits related to the random variation of the input model parameters, because carbonation parameters should be measured at many locations.

In this study, Duracrat's model is chosen as a deterministic model, which integrates parameters relating to the manufacture of concrete and environmental conditions. It is therefore adaptable to a wide range of cement materials that are distinguished by compositions of different cement matrices, conditioned by the nature of the cement, the type of any additions and W / C ratio. Furthermore, its simplicity allows to pair it with a probabilistic algorithm

Duracrat's model gives an expression of the carbonation depth (*Xc*) for a given exposure time *T* by [5,6]:

$$X_C = \sqrt{\frac{2k_e\ k_c D_{eff} C_s T}{a}} \left(\frac{t_0}{T}\right)^{\omega} \tag{2}$$

The time carbonation(*T1*), which is the time necessary so that the carbonation reaches the reinforcement according to the following relations

$$T_1 = \left[\frac{a\ d^2}{2k_e\ k_c\ D_{eff}\ C_S\ t_0^{2\omega}}\right]^{\frac{1}{1-2\omega}} \tag{3}$$

Where:

D_{eff} is the effective coefficient of diffusion of CO_2

$$D_{eff} = 1.6410^{-6}\, \varepsilon_c^{1.8} (1 - RH)^{2.2} \tag{4}$$

ε_c is the porosity of the paste of the carbonated concrete depends on the composition of the concret.

k_e is the factor depending on the climatic conditions, and given by:

$$k_e = \left(\frac{1 - RH_{absol}^5}{1 - RH_{labora}^5}\right)^{2..5} \tag{5}$$

k_c is a parameter taking account of the conditions of curing compound concrete, given by:

$$k_c = \left(\frac{t_c}{7}\right)^{-0.56} \tag{6}$$

Cs is the CO_2 pressure on the surface of the concrete.

T is the expiry considers (year), t_0 is the reference period (28 days), ω is the meso-climatic factor .

a is the quantity of material carbonated.

d is the coating.

III. PROBABILISTIC ANALYSIS OF REINFORCED CONCRETE CARBONATION

The characteristics of the considered medium are:

G/C=3, W/C=0.5, $\rho_W=10^3 Kg/m^3$, ε_c =0.5 ρ_c=3150*Kg/m*, $\rho_G=2400 Kg/m^3$, $d = 3cm$, D_{eff} = 0.46 10^{-8} m²/s, k_c = 3, k_e =0.69, ω=0.1, a =164 kg/m³, $T = 20°C$ and C_S=6.1Kg/m^3.

The mean value of the water to cement ratio is $\mu_{W/C} = 0.5$ and the coefficient of variation $Cv_{W/C}$ varies between 0 and 0.5 [6].

Log-normal distributions are generated, and the deterministic numerical procedure is applied to each individual simulation, providing 10000 values of the depth and time carbonation parameters [7, 8,9].

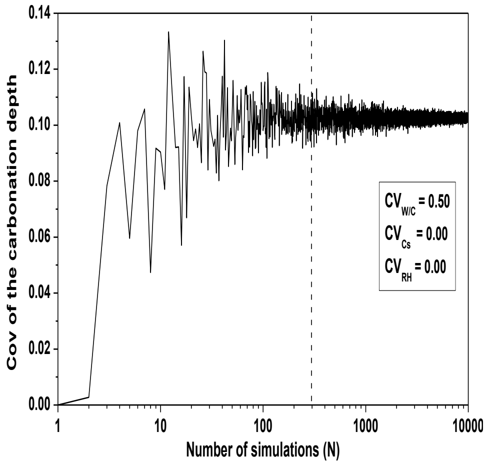
The Water/Cement ratio *(W/C)* is assumed as uncertain with a lognormal distribution. The parameters of the lognormal distribution of *W/C* are expressed as follows:

$$\sigma_{\ln W/C}^2 = \ln\left(1 + \frac{\sigma_{W/C}^2}{\mu_{W/C}^2}\right) \tag{7}$$

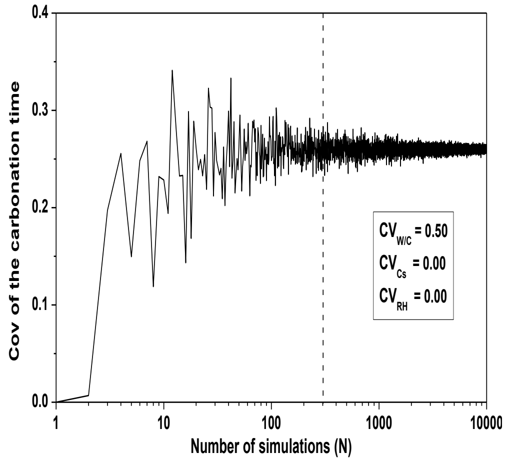
$$\mu_{\ln W/C} = \ln(\mu_{W/C}) - \frac{1}{2}\sigma_{\ln W/C}^2 \tag{8}$$

Where ($\mu_{W/C}$, $\sigma_{W/C}^2$) are statistics (mean and variance) of *W/C*.

The behavior of the coefficient of variation of car bonation depth versus the number of realizations is also investigated, **Figure 1**. ,



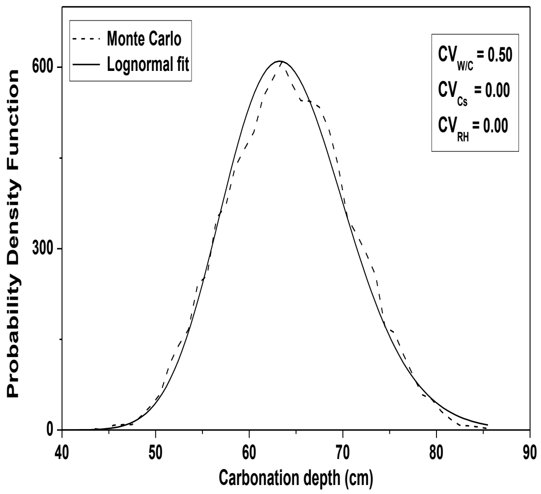
(a) Carbonation depth coefficient of variation versus W/C



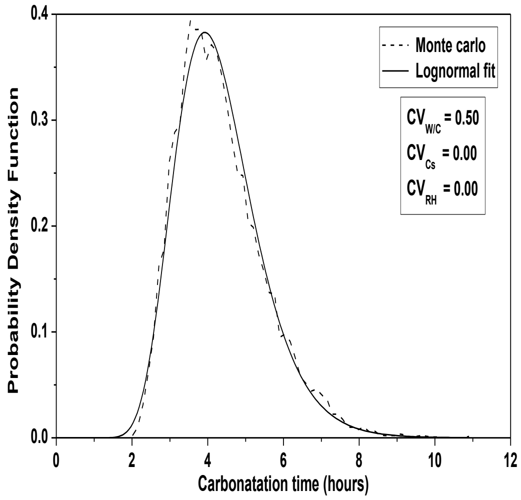
(b). Carbonation time coefficient of variation versus W/C

Fig.1. Carbonation depth and time coefficient of variation versus W/C

The Chi-Square goodness of fit test is used to evaluate the fit of the assumed carbonation parameters probability distribution [10] and the shape of the corresponding his-tograms suggests a log-normal distribution, which is adopted in this study, **Figure 2**.



(a). Probability density function of the carbonation depth versus *W/C*



(b). Probability density function of the carbonation time versus *W/C*

Fig.2. Probability density functions of the carbonation depth and time versus W/C.

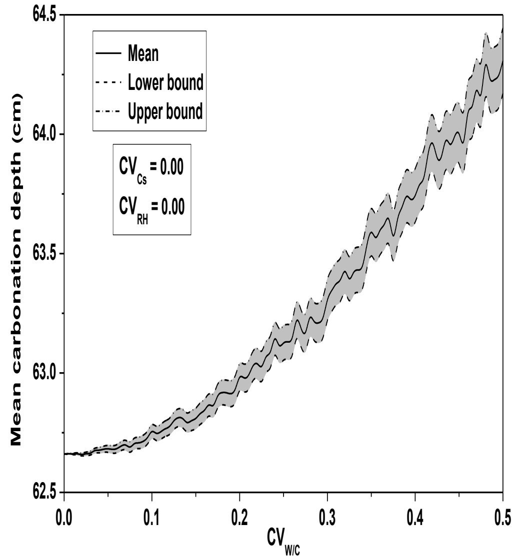
IV. NUMERICAL RESULTS AND DISCUSSION

For an assumed log-normal distribution of W/C, and from the statistics (mean and standard deviation, as well as the 95% confidence interval) of the carbonation depth with respect to *W/C* coefficient of variation $Cv_{W/C}$, it is shown that the mean value is constant for lower values of $Cv_{W/C}$, it increases by 3.28% , see Fig3 (a) and (b). One also notices that the standard deviation increases which indicates that *W/C* variability has a significant effect on the mean carbonation depth and influences strongly its dispersion.

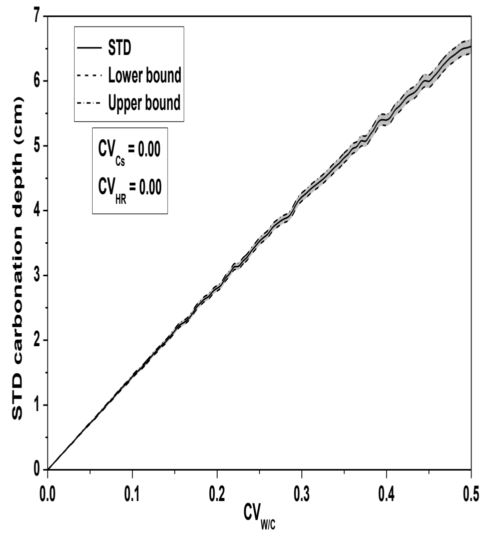
The carbonation kinetic is also affected by pore sizes, the depth of carbonation tends to increase when the porosity of concrete increases.

Measures of mercury porosity (average pore diameter) realized after carbonation show that the solid products of carbonation enough to fill some pores, and taking into account the distribution of pore volumes (and not just the mean pore diameter) suggests that carbonation modifies complexly the pore structure of paste in concrete with the attenuation of certain porous modes and creating new modes and a statistical study of the pore size distribution becomes too complex [10,11].

The speed of concrete carbonation depends mainly on the dioxide carbon penetration inside the cement matrix.



(a). Mean carbonation depth versus W/*C* coefficient of variation



b). STD carbonation depth versus W/*C* coefficient of variation

Fig.3. Carbonation depth statistics and confidence intervals versus W/C coefficient of variation

As the coefficient of variation $Cv_{W/C}$ varies from 0 to 0.5, a decrease in the mean value of the carbonation time of 3.71% is observed, see Fig4 (a) and (b). The confidence interval is important, and constant, indicating that as for carbonation depth, water to cement ratio variability affects the dispersion of the carbonation time, with a weak effect on the mean value.

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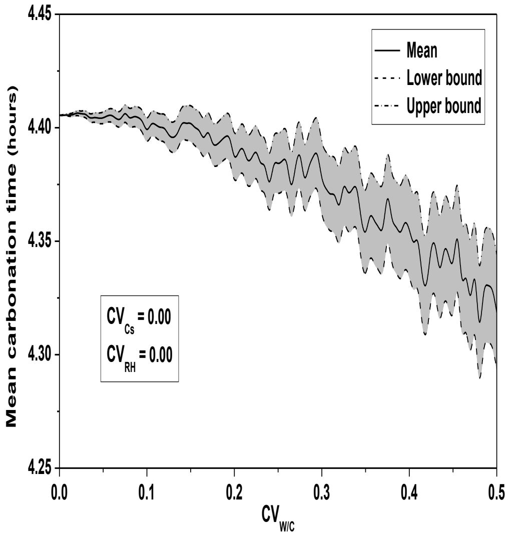
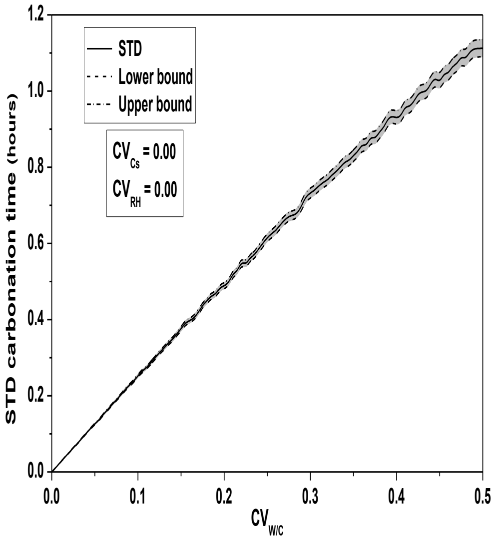


(a). Mean carbonation time versus W/*C* coefficient as variation



b). STD carbonation time versus W/*C* coefficient of variation

Fig.4. Carbonation time statistics and confidence intervals versus W/C coefficient of variation

Indeed, the diffusion of carbon dioxide through the porous structure of concrete is determined by the Water to cement ratio and porosity. More *W/C* ratio is greater, more the amount of free water that can evaporate is important

For a significant porosity and the quantity of carbon dioxide released into the pores is important and time necessary of carbonation T_1 is short.

V. CONCLUSION

The present paper deals with the effect of the Water /Cement ratio randomness on the carbonation depth.

The water to cement ratio variability influences mainly the dispersion of the carbonation depth, but slightly the median value. Statistics values of the carbonation time are independent of the *W/C* coefficient of variation. Indeed, this parameter has an important influence on the interconnection of the porous network, and consequently on the permeability of the concrete and the diffusivity of CO_2 within it.

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