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Incidence of the randomness of the most influential parameters on the reinforced concrete carbonation time

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ABSTRACT

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

The aim of this paper is the evaluation of carbonation time (T_1), which is the time necessary so that the face of carbonation arrives until the reinforcement from a probabilistic analysis. Monte Carlo simulations are realized under the assumption that the Water /Cement ratio, the relative humidity, and the pressure of the carbonic gas on the surface of the concrete are random variables with a log-normal probability distribution.

Keywords: Carbonation time, reinforced concrete, lognormal random variable, Water /Cement ratio, relative humidity, carbonic gas CO_2.

1. INTRODUCTION

Carbonation reaction is due to the calcium carbonates formation by reaction between cements and atmospheric carbon dioxide (CO_2) present in the air , this reaction involves the consumption of alkaline bases present in the interstitial solution of the concretes leading to a reduction in the pH from 13 to lower than 9, the corrosion of the reinforcements can be initiated by the carbonation reaching the reinforcement faces, and a steel depassivation occurs by the reduction in the pH around 9 [1].

Studies of corrosion in reinforced concrete structures require very large specimens due to the heterogeneous structure of the concrete.

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The 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 [2,3,4]. Indeed, the precise knowledge of these parameters requires a probabilistic approach enable to modeling the uncertainties and analyzing their dispersion effect [4].
In this paper, a probabilistic formulation is applied to carbonation phenomenon, and statistics regarding carbonation time are investigated by performing a parametric analysis which integrates the influence of variation coefficient of relative humidity, water to cement ratio and carbonic gas pressure.

2. Probabilistic analysis of concrete carbonation time

The carbonation reaction arises as follows:

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

The electro chemical process arises as follows:

$$Fe + O_2/2 + H_2O \rightarrow Fe^{2+} + 2(OH)^- \quad (2)$$

The Figure.1 illustrates the corrosion rebar process in concrete.
The corrosion of the reinforcements can be initiated by the carbonation reaching the reinforcement faces, this reaction leading to a reduction in the pH from 13 to lower than 9, and a steel depassivation occurs by the reduction in the pH around 9.

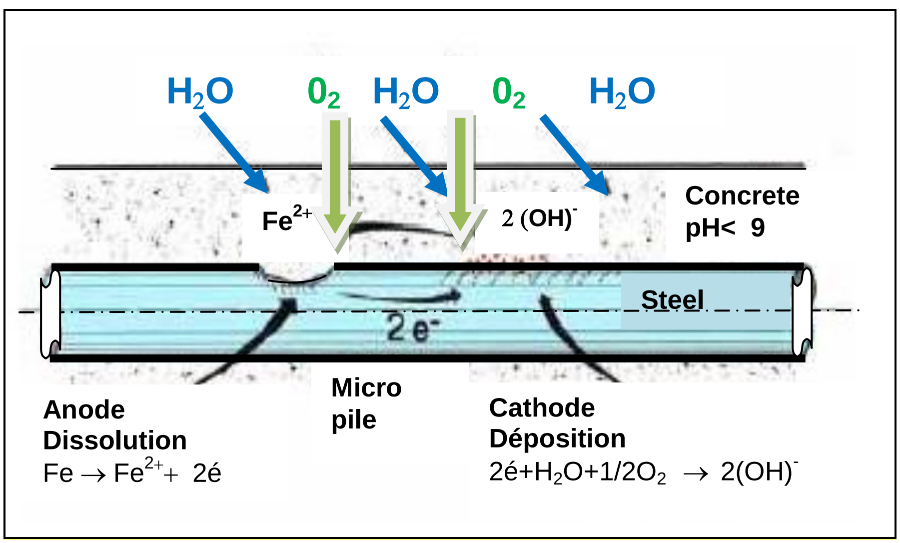


Fig. 1: corrosion rebar process in concrete [5].

2.1 Carbonation time (T_1)

The carbonation rate can be determined from historical data and laboratory testing and the progression of depassivation with time can be calculated [3]. The carbonation time (T_1) is the time required for the face of carbonation to reach the steel, i.e. the time of the beginning of corrosion. This corresponds to the case where the carbonation depth is equal to the concrete cover (*d*).

The Duracrete carbonation model describe the carbonation time by this equation:[6]

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

Where

- a is the quantity of material carbonated given by:

$$a = \frac{\beta_{ch}\, CH\, \alpha_h\, M_{CO2}}{M_{cao}} \qquad (4)$$

M_{CO2} and M_{cao} are the molar masses of carbonic gas and calcite;

α_h is the degree of hydration of cement; $\alpha_h = 80\,\%$

CH is the quantity of the cement Portland;

β_{ch} translates the relation of the portland likely to react; $\beta_{ch} = 85\,\%$

- *d* is the coating,.(*d*=*3*)
- k_e is the factor of environment given by

$$k_e = \left(\frac{1 - RH_{abs}^{5}}{1 - RH_{lab}^{5}} \right)^{2..5} \qquad (5)$$

RH_{abs} and RH_{lab} are the absolute and laboratory relative humidity, respectively.

RH_{abs} = 75%, RH_{lab} = 65%.

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

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

Where t_c is the duration of cure, t_c = 1day and k_c **=** 3

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

$$D_{eff} = 1.6410^{-6}\, \varepsilon_c^{1.8} (1 - RH)^{2.2} \qquad (7)$$

ε_c is the porosity of the paste of the carbonated concrete

For the composition of concrete proposed, the effective coefficient of diffusion can be estimated at D_{eff} = 0.46 10^{-8} m^2/s, with a value of porosity ε_c =0.5

- *Cs* is the CO_2 pressure on the surface of the concrete, *Cs* =6.1 kg/m^3
- T the expiry considers (year),

- t_0 is the reference period (28 days),
- ω is the meso-climatic factor ω=0.1

2.2 Probabilistic analysis

The randomness effect analysis of the Water /Cement ratio (*W/C*), the relative humidity (*RH*), and pressure of carbonic gas (*Cs*) on the reinforced concrete carbonation concentrates on the evaluation of carbonation time (T_1), which is the time necessary so that the face of carbonation arrives until the reinforcement from a probabilistic analysis.
The parameters of the lognormal distribution of *W/C*, *RH* and *Cs* are expressed as. [7,8]

$$\mu_{\ln W/C} = \ln(\mu_{W/C}) - \frac{1}{2}\sigma^2_{\ln W/C} \qquad \sigma^2_{\ln W/C} = \ln\left(1+\frac{\sigma^2_{W/C}}{\mu^2_{W/C}}\right) \qquad (8.a)$$

$$\mu_{\ln RH} = \ln(\mu_{RH}) - \frac{1}{2}\sigma^2_{\ln RH} \qquad \sigma^2_{\ln RH} = \ln\left(1+\frac{\sigma^2_{RH}}{\mu^2_{RH}}\right) \qquad (8.b)$$

$$\mu_{\ln Cs} = \ln(\mu_{Cs}) - \frac{1}{2}\sigma^2_{\ln Cs} \qquad \sigma^2_{\ln Cs} = \ln\left(1+\frac{\sigma^2_{Cs}}{\mu^2_{Cs}}\right) \qquad (8.c)$$

Where $(\mu_{W/C}, \sigma^2_{W/C})$, $(\mu_{RH}, \sigma^2_{RH})$ and $(\mu_{Cs}, \sigma^2_{Cs})$ are statistics (mean and variance) of *W/C*, *RH* and *Cs*, respectively.

Monte Carlo simulations are realized, 10000 independent samples of the parameters *W/C*, *RH* and *Cs* with a log-normal distribution are generated, and the deterministic numerical procedure is applied to each individual simulation, providing 10000 values of the time carbonation parameters [9-10].

Finally, statistics of the time factors (mean, standard deviation and confidence interval) are calculated.

3. Results and discussion

The mean values (μ) and the coefficients of variation (*Cv)* of the different parameters were estimated respectively from Model Code FIB proposals. [11]

$\mu_{W/C}$=0.5 $\qquad$ $Cv_{W/C}$ varies between 0 and 0.5.

$\mu_{RH} = 0.65$. $\qquad$ Cv_{RH} varies from 0 to 0.01

μ_{Cs} = 6.1 kg/m^3 $\qquad$ Cv_{Cs} varies between 0 and 0.5.

The behavior of the coefficient of variation of carbonation time versus the number of realizations is also investigated, **Figure 2**. And the convergence of the final settlement coefficient of variation is observed for a number of realizations N_{samp} around 300, this number is chosen equal to 10000. [12]

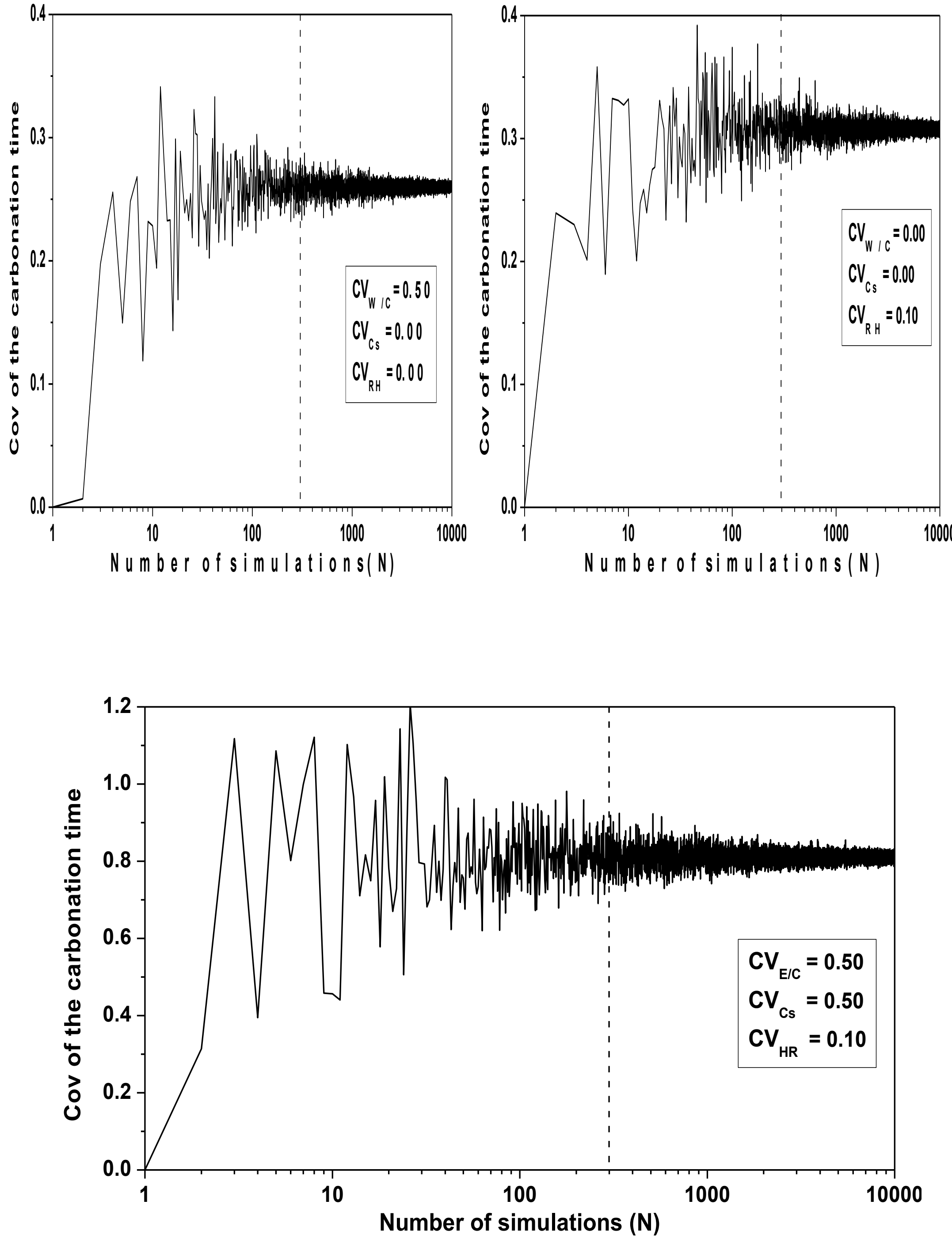
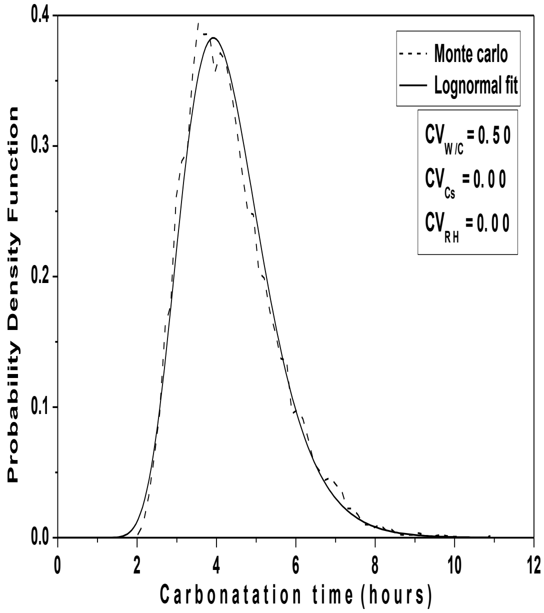
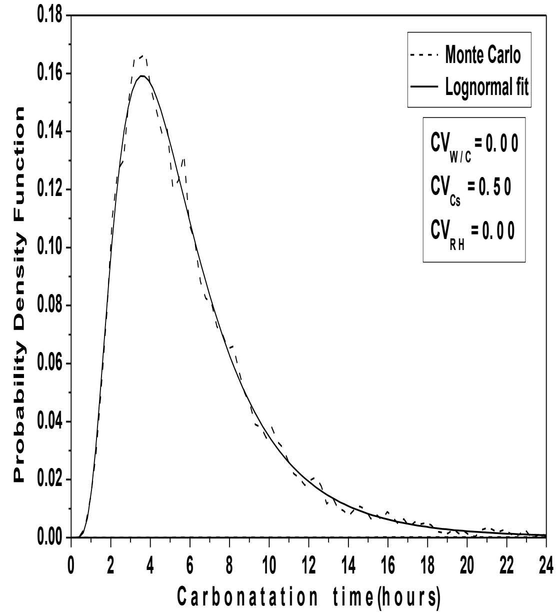


Fig.2. Carbonation time coefficient of variation versus W/*C*, *Cs* and *RH*.

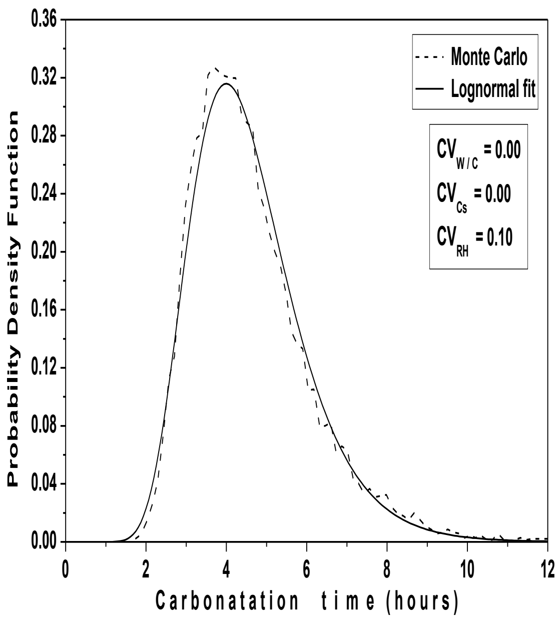
The Chi-Square goodness of fit test is used to evaluate the fit of the assumed carbonation parameters probability distribution [13] and the shape of the corresponding histograms suggests a log-normal distribution, which is adopted in this study, **Figure 3.**



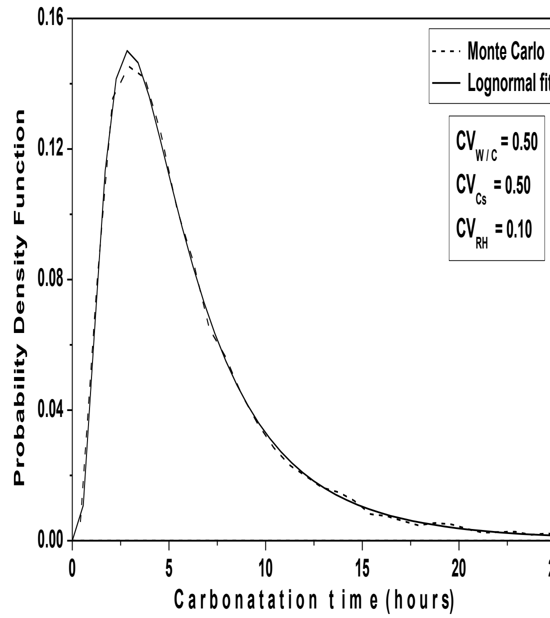
(a). Probability density function of the carbonation time versus *W/C*.



(b). Probability density function of the carbonation time versus *Cs*.



(c). Probability density functions of the carbonation time versus *RH*.



(d). Probability density function of the carbonation time versus W/C,*Cs* and *RH*.

Fig. 3: Probability density function of the carbonation time versus W/*C*, *Cs* and *RH*.

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 Figure.4.

The confidence interval is important, and constant, indicating that water to cement ratio variability affects the dispersion of the carbonation time, with a weak effect on the mean value.

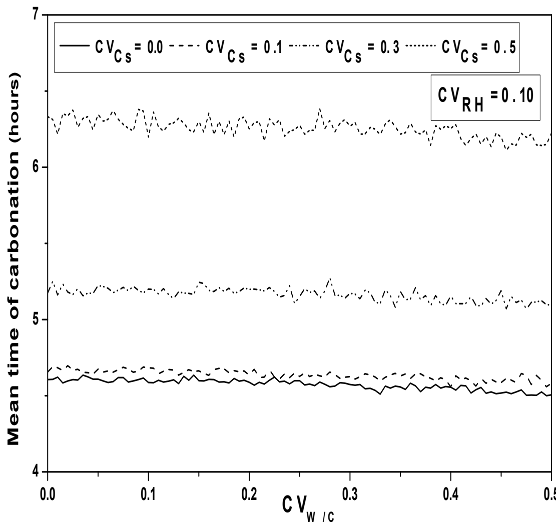
The speed of concrete carbonation depends mainly on the dioxide carbon penetration inside the cement matrix. Indeed, the diffusion of carbon dioxide through the porous structure of concrete is determined by the Water to cement ratio and porosity. More *W/C* ratio is greater, more the amount of free water that can evaporate is important. By evaporation, the water leaves voids and promotes the diffusion of carbon dioxide through the pore network, 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

The carbonation of concrete has an impact on the effective coefficient of diffusion, this coefficient is decreased after the carbonation, and the interaction between the carbon dioxide ions and the surface of calcium silicate hydrates (CSH) negatively charged forms a double layer electric on the surface pores and slows the CO_2 diffusion [14- 15].

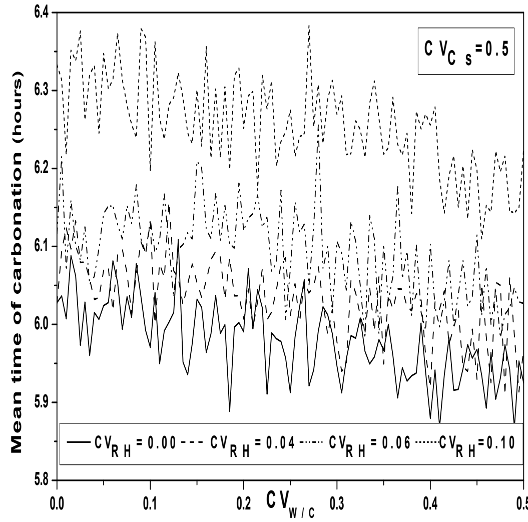
The variation of Cv_{Cs} can be observed in Figure.5. Mean value of the carbonation time increases from 4.51 to 6.17 hours (37%), which indicates that the uncertainty in the CO_2 concentration causes a delay in the carbonation process.

The reaction of hydrated composed of concrete with carbon dioxide induces production of water, more the amount of carbon dioxide released into the pores is greater, more the quantity of water formed during carbonation is important, this training will also disrupt the process in the direction of slower reactions and increase the carbonation time. One notices an important increase of the standard deviation with parabolic curve.

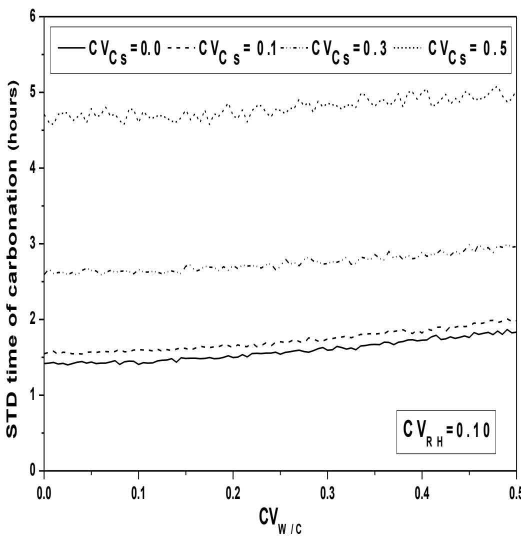
As the Monte Carlo simulations generate samples with broad values and as the coefficient Cv_{RH} varies from 0.0 to 0.1, mean carbonation time increases from 6 to 6.20 hours (2.77%), with an important value of its confidence interval, as showed in Figure.6. The standard deviation curve shows a strong increase with linear variation.



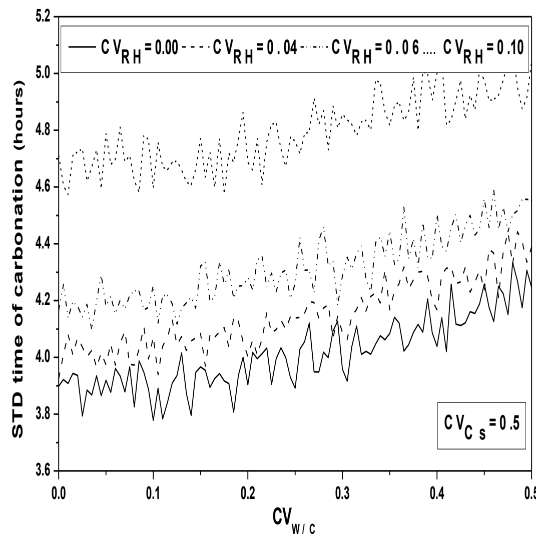
(a) Mean time of carbonation versus W/*C* coefficient of variation.



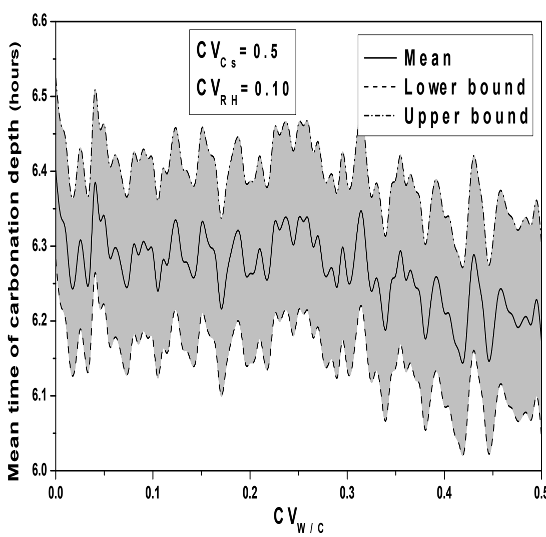
(b) Mean time of carbonation versus W/*C* coefficient of variation**.**



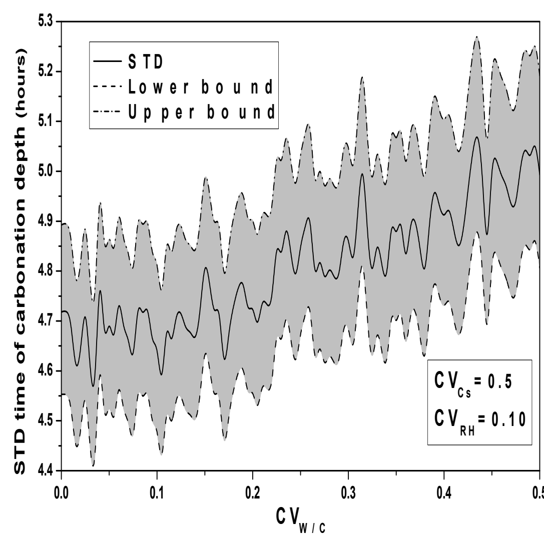
(c) STD time of carbonation versus W/*C* coefficient of variation.



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

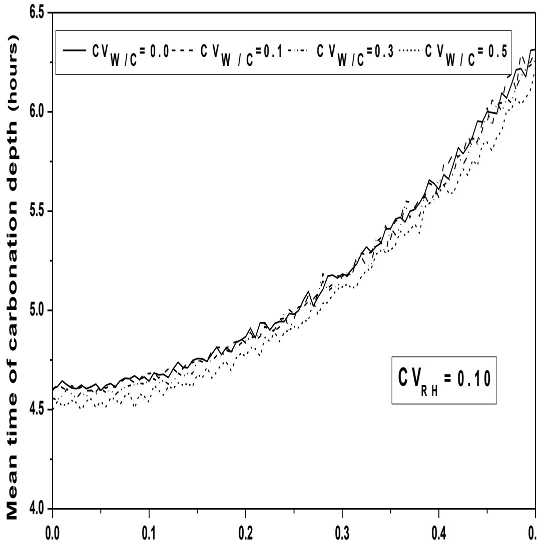


(e) Confidence intervals of Mean versus *W/C* coefficient of variation.

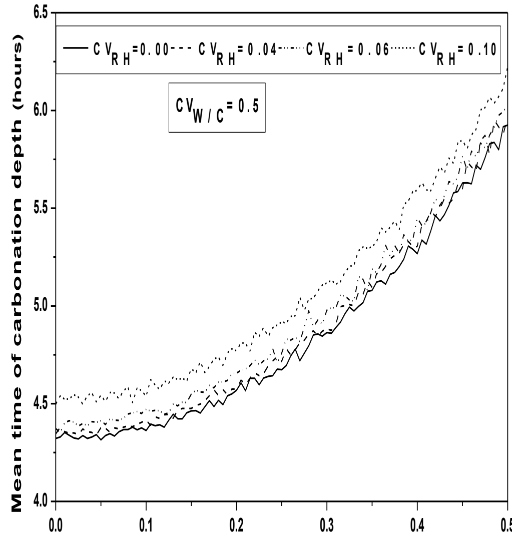


(f) Confidence intervals of STD versus W/C coefficient of variation.

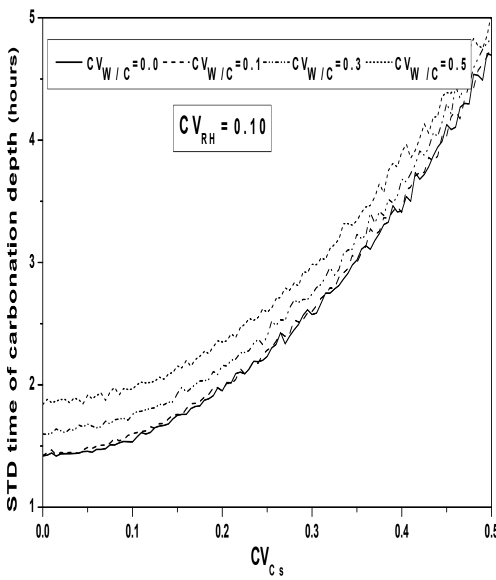
Fig. 4: Carbonation time statistics and Confidence intervals versus W/C coefficient of variation.



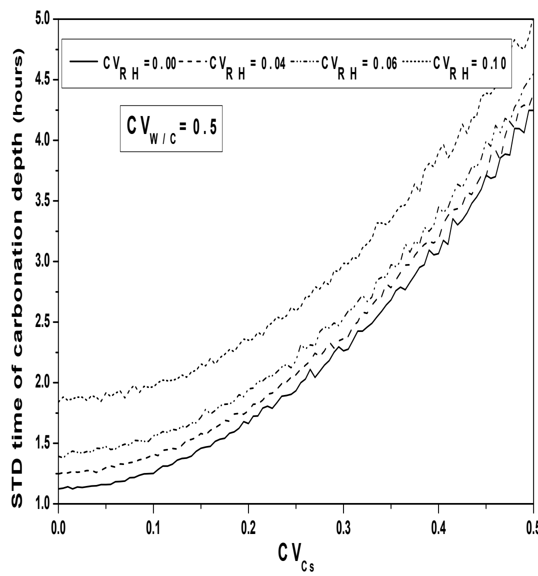
(a). Mean time of carbonation versus *Cs* coefficient of variation.



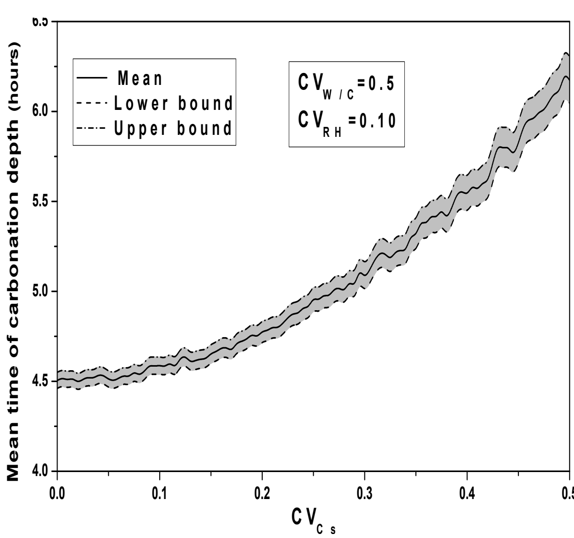
(b). Mean time of carbonation versus *Cs* coefficient of variation.



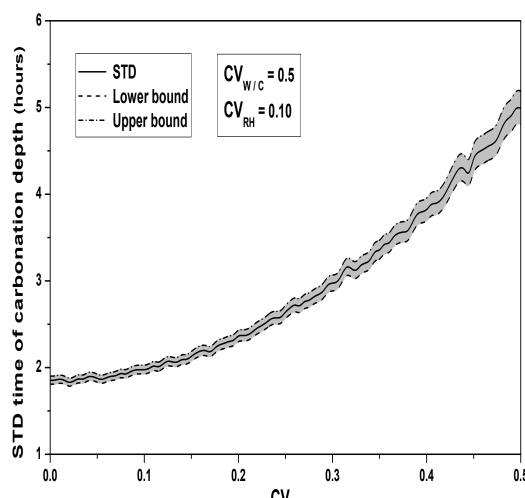
(c). STD time of carbonation versus *Cs* coefficient of variation.



(d). STD time of carbonation versus *Cs* coefficient of variation.

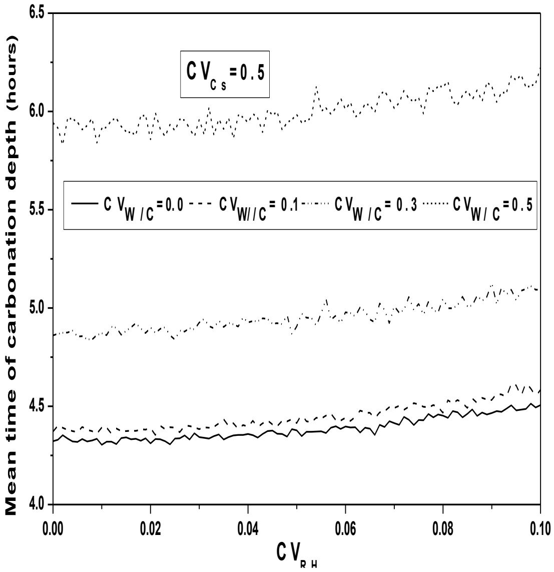


(e) Confidence intervals of Mean versus *Cs* coefficient of variation.

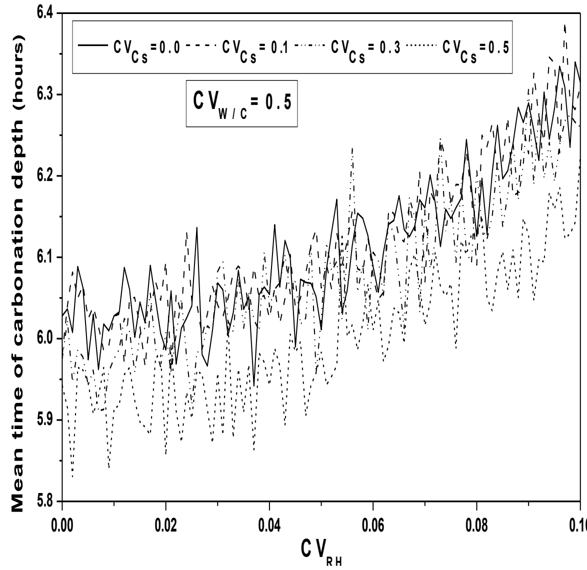


(f) Confidence intervals of STD versus Cs coefficient of variation.

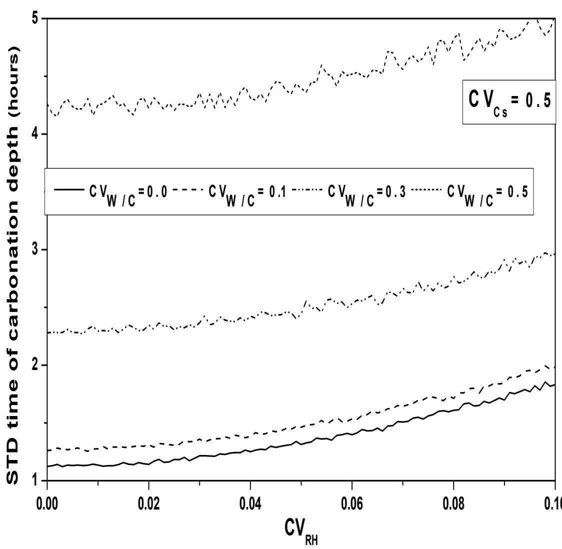
Fig. 5: Carbonation time statistics and Confidence intervals versus Cs coefficient of variation.



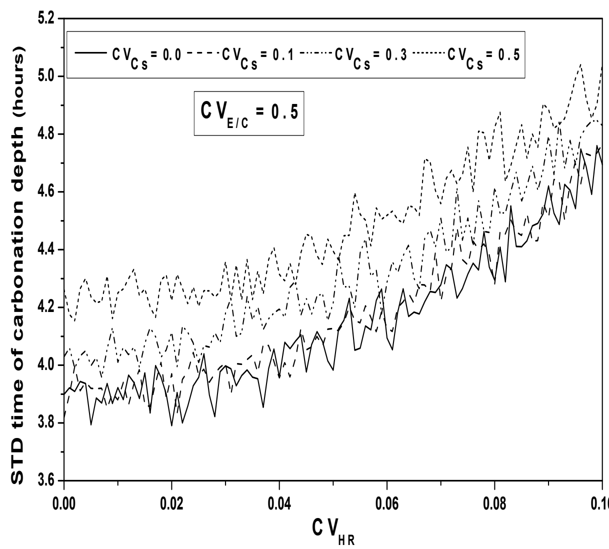
(a) Mean time of carbonation versus RH coefficient of variation.



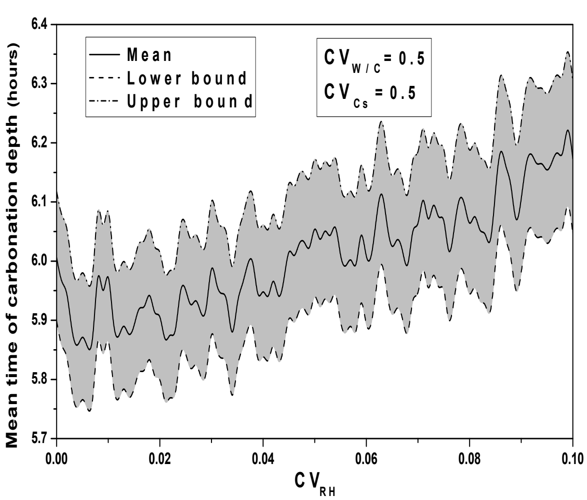
(b) Mean time of carbonation versus RH coefficient of variation.



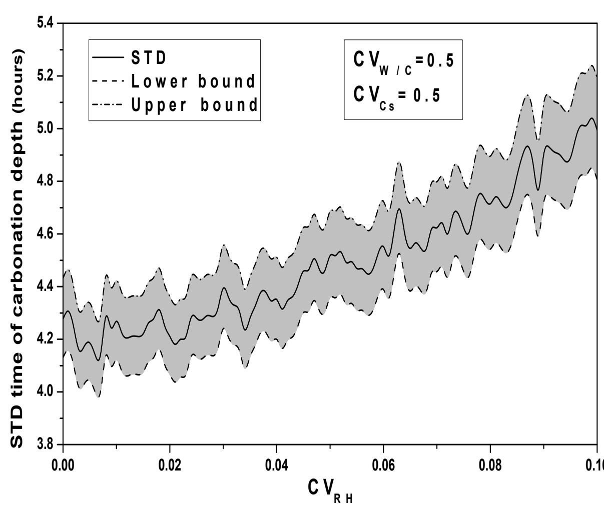
(c) STD time of carbonation versus RH coefficient of variation.



(d) STD time of carbonation versus RH coefficient of variation.



(e) Confidence intervals of Mean versus RH coefficient of variation.



(f) Confidence intervals of STD versus RH coefficient of variation.

Fig. 6: Carbonation time statistics and Confidence intervals versus RH coefficient of variation.

The effect of large values of relative humidity is preponderant over the small values. Variability of *RH* causes a delay in the carbonation process with an increase in the corresponding time with *RH*. High relative humidity values correspond to a high degree of saturation of pore, the diffusion processes of carbon dioxide to the surface reactive minerals becomes extremely low and the associated reaction mechanisms largely unavailable.
A remark can be made here, the coupled effect of the three parameters uncertainty stabilizes the time of carbonation, see Figure.4.e, 5.e, 6.e, indicating that the parameters' randomness act in opposition.

4. CONCLUSION

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.

Variability effect of carbonic gas concentration on the carbonation time is weak; it can be assumed as deterministic for carbonation time.

Variability of the water to cement ratio and the relative humidity influences slightly the carbonation time, whereas the Carbonic gas concentration heterogeneity controls the speed of carbonation by causing a delay in the carbonation process, whereas uncertainties in the three parameters instantly stabilize this time.

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