SERVICE LIFE PREDICTION OF FLY ASH CONCRETE UNDER THE CARBONATION EFFECT

PRÉDICTION DE LA DURÉE DE VIE DES BÉTONS AUX CENDRES VOLANTES SOUS L'EFFET DE LA CARBONATATION

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KELLOUCHE Yasmina[1], GHRICI Mohamed[2], REBOUH Redouane[3]
1 Professor assistant class A, Hassiba Benbouali University of Chlef, P.O. Box 151, Chlef 02000, Algeria- y.kellouche@univ-chlef.dz
2 Professor, Hassiba Benbouali University of Chlef, P.O. Box 151, Chlef 02000, Algeria- m.ghrici@univ-chlef.dz
3 Professor assistant class B, Hassiba Benbouali University of Chlef, P.O. Box 151, Chlef 02000, Algeria- r.rebouh@univ-chlef.dz

Abstract- Carbonation is a chemical phenomenon present in the structure of concrete causing its degradation over time. Once the reinforcement is altered by carbonation, the structure will no longer fulfill the service requirements. The present work consists of estimating the service life of fly ash concrete, by proposing an analytical formula of carbonation depth using STATISTICA software. For this purpose, a database of 300 experimental results was collected from the literature. Six parameters affecting carbonation were used as variables in the proposed formula; binder content, fly ash substitution rate, water/binder ratio, CO_2 concentration, relative humidity and concrete age. The comparison made shows that the carbonation depth formula has a higher correlation (R^2=85%) and lower errors comparing with other models in the literature.Assuming the carbonation depth is equal to the coating thickness under natural carbonation (CO_2=1%), a lifetime formula was extracted by considering the same parameters of the analytical carbonation depth equation. The service life varies according to the fly ash substitution rate, the water to binder (W/B) ratio and the coating thickness; the lower is the W/B ratio and the higher the concrete coating thickness, the longer is the concrete lifespan for all fly ash substitution rates. However, the deduced equation from the carbonation depth model can be used successfully for estimating the service life of fly ash concrete in natural carbonation.

Keywords: concrete, fly ash, carbonation, analytical formula, service life.

Résumé- La carbonatation est un phénomène chimique présent dans les structures en béton provoquant sa dégradation dans le temps. Une fois l'armature altérée par la carbonatation, la structure ne répondra plus aux exigences de service. Le présent travail consiste à estimer la durée de vie d'un béton de cendres volantes, en proposant une formule analytique de la profondeur de carbonatation à l'aide du logiciel STATISTICA. A cet effet, une base de données de 300 résultats expérimentaux a été collectée dans la littérature. Six paramètres affectant la carbonatation ont été utilisés comme variables dans la formule proposée : teneur en liant, taux de substitution des cendres volantes, rapport eau/liant, concentration en CO_2, humidité relative et âge du béton. La comparaison effectuée montre que la formule de profondeur de carbonatation a une corrélation plus élevée (R^2 = 85%) et des erreurs plus faibles par rapport aux autres modèles de la littérature. En supposant que la profondeur de carbonatation est égale à l'épaisseur du revêtement sous carbonatation naturelle (CO_2 = 1%), une formule de durée de vie a été extraite en considérant les mêmes paramètres de l'équation de profondeur de carbonatation analytique. La durée de vie varie en fonction du taux de substitution des cendres volantes, du rapport E/L et de l'épaisseur du revêtement : plus le rapport W/B est faible et plus l'épaisseur du revêtement de béton est élevée, plus la durée de vie du béton est longue pour tous les taux de substitution des cendres volantes. Cependant, l'équation déduite du modèle de profondeur de carbonatation peut être utilisée avec succès pour estimer la durée de vie du béton de cendres volantes en carbonatation naturelle.

Mots clés: béton, cendres volantes, carbonatation, formule analytique, durée de vie.

1-Introduction

Concrete remains the most widely used construction material in the world, despite its vulnerability to degradation phenomena which affects its durability. Therefore, rising maintenance costs have prompted researchers to pay more attention to durability issues in order to extend the life time of constructions. However, it is necessary to understand the deterioration mechanisms that act on these structures and to develop an appropriate model that represents their behavior over time [1]. The service life of reinforced concrete structures can be reduced due to many pathologies; related to design errors during sizing or during execution, shear or flexural strength defects due to excessive loading, as well as the structure aging. In addition, corrosion of reinforcements due to the carbonation of concrete is by far the most encountered problem. It takes place in two distinct stages, an initiation or priming phase also called incubation phase and a propagation phase [2]. The time required for the corrosion to reach the first reinforcement bed by the carbonation effect is much longer than the duration of corrosion propagation[3]. Fagerlund[4]has developed a method for the service life prediction of structures using a relationship between serviceability and time, which can be applied in cases of carbonation, sulfate attack and alkali-reactions. Niu et al. [5] estimated the service life of reinforced concrete structures using the degree of reliability of carbonation over time by applying the limit state equation. Liang et al. [6] have established a relationship between carbonation and age of concrete inspired from the second diffusion Fick law to predict the lifetime of a bridge under corrosion induced by carbonation. Although the expected life of a reinforced concrete structure differs according to its use and size … etc, it is often estimated to be 50 to 65 years, which can be extended to 100 to 120 years for special or important building [7].

Cement additions affect the carbonation of concrete by two phenomena [8-14] : (1) Portlandite consumption due to the pozzolanic reaction, which implies that a small amount of CO_2 is enough to carbonate the remaining hydrates; (2) The modification of the concrete porosity and permeability, which leads to an improvement in the properties of the pozzolanic concrete transport under certain conditions (active pozzolan. long cure time. etc ...).

Indeed, the starting point in material modeling is always a set of experimental results. In the traditional analytical modeling technique, the behavior of the material is observed to identify its characteristics, once done, a mathematical model is developed to simulate this behavior. This process consists of coding behavioral knowledge into a set of mathematical rules.

Andrade et al. [1] combined three modeling techniques (mathematical, statistical and physical-chemical) to predict the service life of reinforced concrete exposed to chloride attacks. They obtained satisfactory results for short durations of exposure than for long durations. The modelling of CO2 diffusion into the metakaolin concretes in the study conducted by Busher et al. [15] showed that the carbonation depth did not exceed 30 mm after 50 years. They concluded that formulations containing metakaolin are more durable than ordinary concretes. Benitez et al. [16] chose the best mathematical model applied for the prediction of the concrete structures service life subjected to carbonation-induced corrosion in the region of Paraguay. One of the most remarkable results given by this study is the reduction of the degradation time between 7 and 10 years depending on the quality of the concrete. The disadvantage of this model is that it is more reliable for sheltered structures than for unsheltered ones. Recently, the predicted and experimental chloride diffusion coefficients along with the service lives of RC structures with different concrete cover and chloride diffusivity were estimated by Homayoonmehr et al. [17] using a full probabilistic model. The results indicated that the corrosion initiation probability was almost similar in both cases. They deducted that the predicted chloride diffusion coefficient can be succefully used in service life prediction of RC structures.

Currently, the challenge for researchers is to extend the life of concrete structures as much as possible under the effect of various degradation phenomena. However, the majority of life estimation models existing in the literature are designed for concretes in marine environments under the effect of chloride ions only [1, 17]. In addition, most models are complicated and difficult to apply. Given that carbonation plays an essential role in the durability of reinforced concretes, this paper consists in estimating the lifetime of concrete containing different substitution rates of fly ash, by predicting carbonation depth using an analytical model. This model introduces the parameters influencing the carbonation such as the binder content (B), the fly ash percentage (FA), the water to binder ratio (W/B), the CO_2 and the relative humidity (RH) concentrations. Both developed equations could be used to estimate the carbonation depth and the lifetime of fly ash concrete without passing by laboratory tests which are very costly and time-consuming.

2-Data collection and analysis

Carbonation depth data of fly ash concrete was extracted and compiled from literature research projects to build the database of 300 data [13, 18-28]. Six parameters were considered to build the database, including binder content (B), fly-ash percentage (FA), water-to-binder ratio (W/B), CO_2 concentration, relative humidity (RH), and time of exposure (t), the output was carbonation depth (d) measured under 28 days of wet cure. The source of data and their distribution and statistic properties are summarized in Tables 1 and 2, respectively.

Table. 1. Source of data

Tableau 1. Source des données

Authors	ND	DD (%)	Fly ash (%)	Binder (kg/m^3)	W/B	CO_2 (%)	HR (%)	t (days)	d (mm)
Burden [12]	76	25	30-50	340-	0.34-	1	65	7-90	0.0-7.0
Younsi [13]	14	5	0-50	301-	0.41-	50	65	7-42	11.0-26.5
Atis [18]	05	2	0-70	400	0.30-	5	65	14	2.1-7.3
Khunthongkeaw et al	24	8	0-30	288-	0.50-	4	55	30-60	7.0-18.8
Sulapha et al. [20]	84	28	0-30	300-	0.40-	6.5	65	14-	0.0-35.2
Sisomphon and Franke	12	4	0-50	300-	0.42-	3	65	7-63	3.0-16.0
Lammertijn and De	24	8	0-67	400	0.40	10	60	7-126	0.1-57.0
Jiang et al [23]	16	5	0-40	340	0.45	3 -	70	3-28	7.7-22.4
Emmanuel et al. [24]	04	1	0-30	260-	0.58-	50	65	28	4.0-9.0
Hui et al. [25]	16	5	0-25	312-	0.39-	20	70	30-	13.8-28.5
Das and Pandey [26]	10	3	0-35	384	0.37-	10	65	30	1.3-5.0
Peng and Qingfu [27]	05	2	0-25	494	0.32	20	70	24	2.3-3.5
Van and De Belie [28]	10	3	0-50	225-	0.35-	10	60	7	0.0-14.7
Total	300	10	/	/	/	/	/	/	/

ND: Number of Data; DD: Distribution Data percentage

Table 2 : Distribution and statistic properties of data

Tableau 2 : Distribution et propriétés statistiques des données

	Binder (kg/m^3)	FA (%)	W/B	CO_2(%)	RH (%)	√t	X_c (mm)
Minimum	260	0	0.28	1.0	55.00	1.73	0.36
Q1	340	0	0.40	1.0	65.00	4.58	1.94
Median	350	20	0.45	6.5	65.00	6.48	5.78
Q3	400	40	0.50	10.0	65.00	9.49	14.52
Maximum	500	70	0.63	50.0	70.00	19.08	50.23
Mean	370	21	0.45	9.1	64.25	7.62	9.05
Range	240	70	0.35	49.0	15.00	17.35	49.87

Q1 Quartile 1; Q3 Quartile 3

3-Proposal of analytical formula

Based on the 1st Fick's law X (t) = A√t, Saetta and Vitaliani [29] proposed a formula according to the parameters influencing carbonation (Eq.1):

$$A = f_{mat}.\left(B \times \frac{W}{B} \times FA\right).f_{env}.(CO_2 \times RH \times T).f_{cure} \qquad (1)$$

With; f_{mat} material parameters function (B, W/B, %FA). f_{env} environmental parameter's function (CO_2, HR, T) and f_{cure} cure conditions function. In our case, we only consider the parameters we introduced as input neurons in the artificial neural networkmodel [30] (B, W/B, FA, RH, CO_2 and t) to develop the analytical formula.

According to the results of previous experimental research, it has been observed that increasing the W/B ratio and CO_2 concentration increases the depth of carbonation [18-20]. While increasing the binder content, the depth of carbonation gradually decreases[12, 18, 20]. On the other hand, the relative humidity increases the depth of carbonation in a well-specified range of variation (50%-70%) and it is almost zero when approaching 0% and 100% of RH [31]. In addition, cementitious additions have a contradictory effect ; they accelerate the carbonation process by pozzolanic reactions by consuming more portlandite, and they densify the cement matrix by the production of CSH hydrates and form more calcite [31]. Based on these results, and taking Saetta's formula as basis, the studied parameters have been placed in equation (1) and thus the coefficient A is proposed as the ratio between these parameters. For this purpose, an expression of the following form was chosen [32] (Eq.2):

$$A = \frac{\left({}^{W}/_{B}\right)^{\alpha} \times (CO_2)^{\beta}}{(B)^{\gamma} \times (1-RH)^{\delta} \times (1-FA)^{\theta}} \qquad (2)$$

The non-linear estimation was used to find a best-fit value of $\alpha, \beta, \gamma, \delta$ and θcoefficients by using regression analysis in the *Statistica* 12 software that facilitates the identification of statistical model coefficients. To assess how the equations fit to the experimental data, the coefficient of correlation was used.

The best correlation obtained was that of Eq. (3):

$$X_C = \frac{\left({}^{W}/_{B}\right)^{1.93} \times (CO_2)^{0.43}}{(B)^{0.08} \times (1-RH)^{1.76} \times (1-FA)^{1.94}} \sqrt{t} \qquad (3)$$

This equation is the formula proposed to measure the carbonation depth of fly ash concrete for different concrete composition (B, FA and W/B), under different atmospheric conditions (RH and CO_2) at any exposure time (t).

4-Validation of the proposed formula

The validity of the carbonation-depth formula of fly-ash concrete (Eq. 3) for new data issued from other research results [33-36]needs to be verified. For this purpose, a comparison between the calculated values by the proposed formula and those predicted by the artificial neural network model elaborated in Kellouche et al. [30] paper and the obtained data using the Papadakis model [31] was made. The Papadakis model was selected because it's the only model for fly-ash concrete carbonation depth prediction that considers the same parameters as in our investigation (Eq.5).

The Papadakis carbonation depth X_c(m), is calculated using the following equation[31]:

$$X_c = \sqrt{\frac{2D_{e,CO2}\left({CO_2}/_{100}\right)t}{0.33CH+0.214CSH}} \qquad (4)$$

Where CO_2 is the atmospheric carbon dioxide concentration (%), $D_{e,CO2}$ is the effective diffusivity of CO_2 (m^2/s) and CH, C-S-H are hydrates quantities in kg/m^3 of concrete.

Under ambient environmental conditions, the $D_{e,CO2}$ can be estimated by the following empirical equation (Eq.5):

$$D_{e,CO2} = A\left(\frac{\varepsilon_c}{\frac{C}{\rho_C}+\frac{FA}{\rho_{FA}}+\frac{W}{\rho_W}}\right)^a \times \left(1-{RH}/_{100}\right)^b \qquad (5)$$

Where C, FA and W are the cement, fly-ash and water content in kg/m^3 respectively, ρ_C, ρ_{FA}, and $\rho_W$are the cement, fly-ash and water density respectively, $\varepsilon_c$ia the total porosity of carbonated concrete and RH is the relative humidity (%). A, a, and b are parameters obtained from regression analysis of experimental data respectively equal to 1.64×10^{-6}, 1.8, and 2.2, for $0.5<W/C<0.8$, and 6.1×10^{-6}, 3, and 2.2, for $0.38<W/(C+kP)<0.58$, where k is the fly-ash efficiency factor in terms of the 28-day compressive strength (equal respectively to 0.5 and 1 for fly ash with low CaO and fly ash with High CaO) and P fly ash replacement level [31].

The quantities of CH and C-S-H hydrates, for a complete cement hydration and pozzolanic reaction are given as follows (Eqs. 6-11):

For low-Ca fly-ash concrete

$$CH = 0.30 - 1.30FL \qquad (6)$$

$$C-S-H = 0.57C - 1.25FL \qquad (7)$$

$$\varepsilon_c = (W - 0.268C - 0.177FL)/1000 \qquad (8)$$

For High-Ca fly ash concrete

$$CH = 0.29C - 0.50FH \qquad (9)$$

$$C-S-H = 0.57C - 0.79FH \qquad (10)$$

$$\varepsilon_c = (W - 0.267C - 0.203FH)/1000 \qquad (11)$$

The comparison between the proposed formula results, the ANN model results [30] and those of Papadakis [31]are summarized in Table 3. The correlation between experimental and predicted results is illustrated in Fig.1.

Table 3 : Comparison of predicting and experimental results

Tableau 3 : Comparaison entre les résultats prédits et expérimentaux

MAE: the mean absolut error, MAPE: the mean absolut percentage error and RMSE: the root mean square error

	MAE	MAPE	RMSE	R^2
ANN model	1.24	4.26	58 %	0.86
Papadakis model (Eq. 4)	9.59	15.4	153 %	0.75
Proposed formula (Eq. 3)	2.05	7.38	37 %	0.85

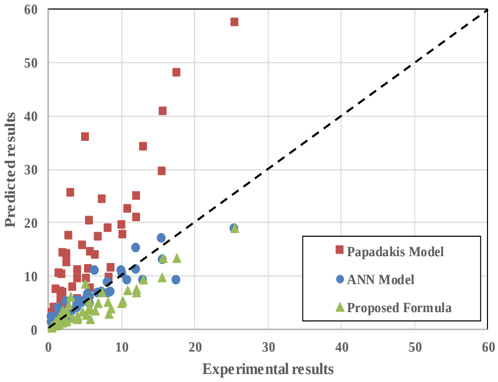


Figure1: Comparison of predicting and experimental results

Figure 1: Comparaison entre les résultats prédits et expérimentaux

The Papadakis model [31] gave the lowest determination coefficient (75%), while the proposed formula and the ANN model [30] had almost the highest coefficients of 86% and 85%, respectively. By comparing the mean absolut error (MAE), the mean absolut percentage error (MAPE) and the root mean square error (RMSE) of the three models, it's observed that the ANN model is the most accurate model with the lowest errors, whereas the Papadakis formula has reached the highest errors. However, errors obtained for the proposed formula (Eq.3) are very close to those of the ANN model.

This result confirms that the proposed formula is more efficient than the semi-empirical model proposed by Papadakis which overestimated the results. According to Sabet and Jong [37], this overestimation is due to the steaming of samples at 105 °C during preconditioning, which led to accelerate carbonation and give much higher results.

The found results indicate that the proposed formula (Eq.3) has a certain performance and can be used to predict the fly ash concrete carbonation depth in the same variation range of parameters affecting the carbonation of fly concrete as mentioned above. estimate the carbonation depth of fly ash concrete without passing by laboratory tests which are very expensive and time-consuming to develop.

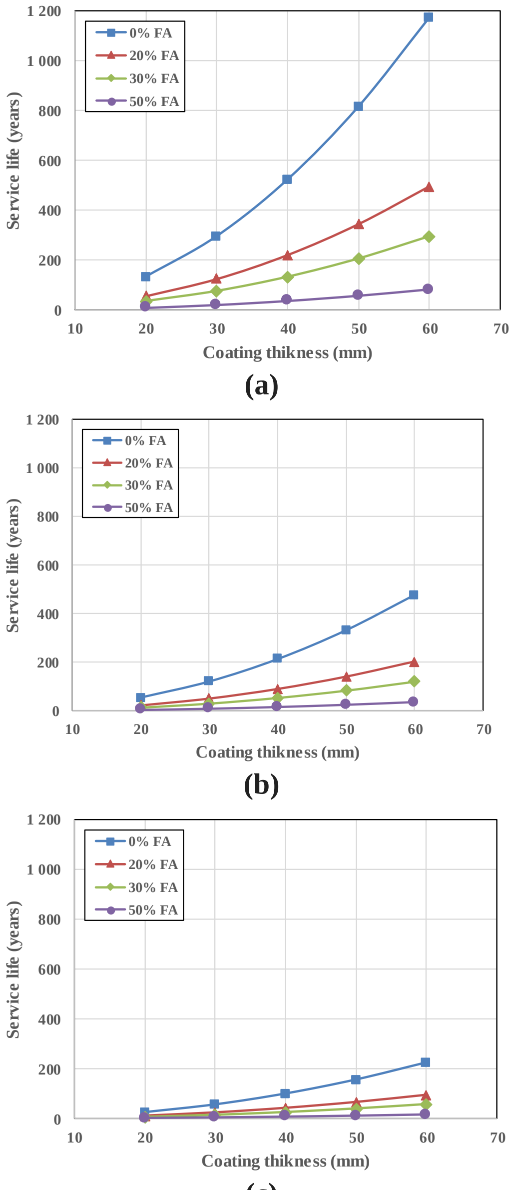
5-Service life prediction of fly ash concrete

Carbonation is manifested in concrete in two successive phases [2]. The first named the incubation phase; the carbon dioxide diffuses through the concrete pores until it reaches the first reinforcement bed after a time of incubation for a carbonation depth $X_c = e$, where “e” is the concrete coating. The second phase called the propagation phase; the carbonation propagates by going beyond the reinforcements with the decrease of the pH up to values lower than 9. This carbonation process tells us that the most important phase that we must take in consideration for estimating the service life concrete is the incubation phase.

The formula proposed in this study has been applied to accelerated carbonation results, but to estimate the lifetime (incubation) it is necessary to convert the accelerated carbonation depth to natural carbonation depth. Researchers have found good correlations between accelerated carbonation and natural carbonation [19],only that the relationships derived from these studies are applicable for their own results. Recently, Czarnecki and Woyciechowski[38]found that accelerated carbonation depth for CO_2 = 1% is identical to that of natural carbonation. From Eq. (11), assuming the carbonation depth (X_c) is equal to the coating thickness (e) and considering the deduction of Czarnecki and Woyciechowski [38], the duration of the incubation phase can be estimated by Eq. (12):

$$t_{incubation} = \left(\frac{(B)^{0.08} \times (1-RH)^{1.76} \times (1-FA)^{1.94}}{\left(W/_B\right)^{1.93} \times (CO_2)^{0.43}} \times e \right)^2 \qquad (12)$$

Assuming a fly ash concrete exposed to natural carbonation (CO_2 = 1%) and a relative humidity of 65%. The service life varies according to the fly ash substitution rate, the W/B ratio and the coating thickness e as shown in Figs. 2 (a, b and c).



(a)

(b)

(c)

Figure 2: Service life of fly ash concrete: a) W/B=0.4; b) W/B =0.5 and c) W/B =0.6

Figure 2: Durée de vie du béton aux cendres volantes: a) E/L=0.4; b) E/L=0.5 et c) E/L=0.6

The W/B ratio plays a very important role in the service life of concrete with and without fly ash; the lower it is the more the concrete has a longer life, because of the densification of the microstructure which prevents the penetration of aggressive agents such as CO_2. For the different W/B ratios (0.4, 0.5 and 0.6), the service life increases with the increase of the coating thickness, which represents a reinforcement protection envelope: For a coating thickness ranging from 20 to 60 mm. the lifetime of a concrete without additions varies from 150 to 1200 years, 100 to 450 years and 25 to 220 years old for 0.4, 0.5 and 0.6 W/B ratios, respectively. The substitution of cement by fly ash decreases the lifetime of fly ash concrete, this decrease is much more appreciable for higher substitution rates (40 and 60%). From Fig. 2 (a), it can be deduced that the substitution of cement with 20% FA and a coating of 30mm can give a concrete of the same lifetime as a control concrete with a coating of 20mm. Beyond 30mm of coating, the lifetime of concrete with 20% FA substitution exceeds 200 years. Comparing Figs. 2 (a and b), it's noted that the lifetime of concrete with 20% FA replacement and 0.4 W/B ratio is the same as that of concrete without additions and with 0.5 W/B ratio for the different coating thicknesses.

6-Conclusions

The present work consists of estimating the service life of fly ash concrete, by proposing an analytical formula of carbonation depth. The following conclusions have been drawn:

- The comparison made shows that the carbonation depth formula has a higher correlation (R^2=85%) and lower errors comparing with other models in the literature;

- The experimental validation of the obtained formula proves that it can be used to predict the carbonation depth of fly ash concrete without passing by laboratory tests.

- Assuming the carbonation depth (Xc) equal to the coating thickness (e) and considering the fly ash concrete exposed to natural carbonation (CO_2=1%), the duration of the incubation phase (service life) has been estimated by a mathematical formula with the same performance of that of the carbonation depth formula.

- Assuming a fly ash concrete exposed to natural carbonation and a relative humidity of 65%, the predicted service life varies according to the fly ash substitution rate, the W/B ratio and the coating thickness "e"; the lower is the W/B ratio and the higher the concrete coating thickness "e", the longer is the concrete lifespan for all fly ash substitution rates.

- The substitution of cement by fly ash decreases the lifetime of fly ash concrete, this decrease is much more appreciable for higher substitution rates (40 and 60%).

- The concrete lifespan containing 20% FA replacement with 0.4 W/B ratio is the same as that of plain concrete with 0.5 W/B ratio for the different coating thicknesses.

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