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APPLICATION OF CARBONATION MODEL FOR SERVICE LIFE DESIGN TO SERBIAN ENVIRONMENTAL CONDITIONS AND ENGINEERING PRACTICE

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Abstract

This paper highlights the application of carbonation model for service life design to local, Serbian environmental conditions and engineering practice. The basis of service life design using probabilistic approach and the deterioration model are presented. According to the data obtained from different sources, the varying range of each parameter typical for the local environmental and execution conditions (Belgrade, Serbia) was estimated. Therefore, instead of using probability distribution functions and characteristic values for some of the parameters, suggested mean values can be adopted for the local area. In addition, the influence of each parameter on the carbonation depth was estimated.

1. INTRODUCTION

Since concentration of atmospheric carbon dioxide (CO_2) has been constantly increasing and that most of our structures are being built in urban environment, the carbonation process should be considered as one of the main causes for deterioration and the major concern of durability design of reinforced concrete structures nowadays. Therefore, carbonation induced corrosion is the focus of investigation presented in this paper.

Traditionally, the durability design of concrete structures is based on implicit and experience based rules for materials, material composition, working conditions, structural dimensions, etc. According to the Serbian national design code BAB'87 [1], these requirements are related to the type of environment exposure, crack width limitation and minimum concrete cover as main 'deem to satisfy' design rule. On the other hand, additional limitations such as maximum water to cement ratio, minimum cement content, air content and cement type are proposed by European design code [2]. The purpose of all these rules is to secure the robustness of the structure, although it is not possible to conduct durability design for intended service life or to give explicit relationship between performance and remaining

service life [3]. As a consequence, this approach, based on experience has to be modified and replaced by durability design comparable to load design as we are used to have in our codes.

In general, the failure probability (probability that the "load", exceeds the "resistance") must be limited to a target probability [4,5]. When carbonation as the deterioration mechanism is concerned, "resistance" corresponds to the value of concrete cover (a), while the value of carbonation depth (x_c) represents the "load". There are a number of models, dependent on different parameters, describing the propagation of carbonation process in concrete and giving the prediction of carbonation depth in course time t (x_c (t)), [4,5,6,7]. One of them has been developed within the research project Dura Crete [5] and slightly revised in the research project DARTS [4]. This model is proposed by recently presented final draft of Model Code [8]. The calculation of carbonation depth is based on diffusion process as the prevailing transport mechanism within the concrete:

$$x_c(t) = \sqrt{2 \cdot k_e \cdot k_c \cdot \left(k_t \cdot R_{ACC,0}{}^{-1} + \varepsilon_t\right) \cdot C_S} \cdot \sqrt{t} \cdot W(t) \qquad (1)$$

x_c (t)- carbonation depth at the time t, [mm]
t- time of exposure, [years]
k_e- environmental function, [-] →relative humidity of environment, RH_{real}
k_c- execution transfer parameter, [-] →curing period of concrete
k_t- regression parameter, [-] →experimental value
$R_{ACC,0}{}^{-1}$- inverse effective carbonation resistance of concrete, [(mm^2/year)/(kg/m^3)] → w/c ratio and type of cement
ε_t - error term, [-] →experimental value
C_S - CO_2 concentration, [kg/m^3]
W(t) - weather function, [-] →time of wetness ToW, probability of driving rain p_{SR}

This model is relatively complicated because it takes into account large number of parameters- material ($R_{AAC,0}{}^{-1}$), environmental (RH, C_S, ToW, p_{SR}), execution (k_c), test (k_t, ε_t). According to principles of reliability, each parameter has to be presented with appropriate distribution function (full probabilistic design method), or more often with characteristic value (semi probabilistic, i.e. partial factor method). Regardless of the method being used, huge database is needed and the only difference is concerning data proceeding procedure. This paper intends to answer the question whether is it possible to use mean values of some of the parameters (for local conditions) if their impact on calculated carbonation depth is small. Even Model Code [4] approves this simplification, dividing parameters into governing ones (which need statistical evaluation and/or partial factor values) and those that can be taken as the mean values. This approach tends to facilitate and make durability design suitable for engineering practice without repeating unnecessary statistical evaluations again and again. Therefore, the analysis of each parameter from expression (1) and calculation of the representative values, having in mind local (Serbian) environmental conditions and engineering practice, will be presented in the following.

2. ANALYSIS OF PARAMETERS

2.1 Environmental function, k_e

The environmental function, k_e, (eq. 2), takes into account the influence of the humidity level on the diffusion coefficient and hence on the carbonation resistance of the concrete.

$$k_e = \left(\frac{1 - \left(\frac{RH_{real}}{100} \right)^{f_e}}{1 - \left(\frac{RH_{ref}}{100} \right)^{f_e}} \right)^{g_e} \quad (2)$$

RH_{real} is the relative humidity of the carbonated layer [%], RH_{ref} is the reference relative humidity- 65% , f_e and g_e are exponents with values 5.0 and 2.5, respectively.

Instead of relative humidity of the carbonated layer, relative humidity of the ambient air of the structure (RH) is suggested to be used due to difficulties in obtaining the value of RH_{real} [4]. Further on, RH_{real} is equal to RH. The maximum value of 1.4 for k_e, practically corresponds to all values of relative humidity lower than 50%, while for higher values of RH the function k_e gradually decreases indicating that carbonation process is slowed down.

According to the data from the Belgrade weather station [9], the average annual values of relative humidity vary in narrow range between 62% and 73%, with standard deviation of only 2.5%. Values of environmental function, k_e, are obtained by inserting these relative humidities in eq. (2). It results in relatively large changes of about 41% in value of parameter k_e. The changes of carbonation depth would be even larger if, instead of mean yearly values, monthly or even daily values of the relative humidity were taken into account. This is due to the fact that their standard deviation is larger, e.g. mean monthly values of RH change from 61% in December up to 80% in April. Although Model Code [4] recommends taking daily mean values for quantification, this base is too huge and, having in mind usual target service life (several tens of years), is considered to be inappropriate.

2.2 Execution transfer parameter, k_c

The environmental function k_c takes into account the influence of concrete curing on the effective carbonation resistance. The environmental function k_e is described according to (3):

$$k_c = \left(\frac{t_c}{7} \right)^{b_c} \quad (3)$$

,where k_c is execution transfer parameter [-], b_c is exponent of regression (mean value μ= -0,567, standard deviation σ= 0,024) [-] and t_c is period of curing [day].

The influence of concrete curing period is enormous - decreasing the number of curing days leads to significant increase in value of execution function. Therefore, in case of reducing the curing period from 7 to 1 day, the value of parameter k_c increases 3 times and leads to increase of carbonation depth up to 73%. Indicated by the BAB'87 [1], curing period in normal conditions is 3 days, while in hot conditions is 7 days. Based on experience and author's knowledge, in Serbian engineering practice, duration of curing period is in range between 2 and 3 days. Even minimum difference of one curing day (in this interval of 2-3 days) increases the value of carbonation depth by 12%. Due to the fact that number of curing days can be prescribed value (by the designer), this parameter may be taken as constant value.

2.3 Environmental impact C_s

The CO_2 concentration represents the direct impact of the environment on the reinforced concrete structures and, therefore, main trigger for carbonation process, which is accelerated by increasing the CO_2 concentration around the considered structure. Ten years ago, global

CO_2 content in the atmosphere was detected to be in a range of 350-380ppm (parts per million) [4]. For usual structures, the reference value of Cs is the CO_2 concentration in atmosphere of the local area around the analyzed structure (if those data are available). However, for road tunnels, chimneys, structures exposed to effects of usage of combustion engines (public garages) etc. value of Cs is obtained by adding the concentration of CO_2 due to emission source to the CO_2 concentration in atmosphere. This is very important because the total concentration of CO_2 can be as much as 10 times higher than the average concentration in atmosphere, which enlarges carbonation depth up to around 3 times. Therefore, in urban environments even few times higher concentrations are expected [10], while in rural areas (300 ppm) and seaside areas (224 ppm) the concentrations are lower than normal [11]. However, the data for analyzed local area (Belgrade, Serbia), according to the author's best knowledge, are not available. What we do have are CO_2 concentrations from urban areas in Europe: Madrid (558ppm), Lisbon (433ppm), Rome (505ppm), Krakow (440ppm) and Paris (up to 950ppm) [10, 12]. Considering facts such as fast growing population, heavy road traffic, extensive use of private cars and raise of mechanized industry typical for Belgrade urban environment, even higher concentration of carbon-dioxide could be expected than in those cities. Increase of CO_2 concentration of around 1.5 ppm/year [4], should also be taken into account during the estimation of environmental impact Cs on observed structure. Having in mind previously stated facts, author's suggestion is to adopt the double value of mean global concentration, i.e.700 ppm, which would be appropriate for Belgrade urban environment.

2.4 Weather function

The weather function W takes into account the meso-climatic conditions due to wetting events of the concrete surface and is calculated according to the following equation (4):

$$W = \left(\frac{t_0}{t}\right)^{\frac{(p_{SR}\cdot ToW)^{b_W}}{2}} \tag{4}$$

t_0 –	time of reference,	28 [days]→0.0767	[years]
t –	time		[years]
ToW –	time of wetness		[-]
	("decisive" rain event-days with rainfall≥2.5 mm/m^2)/365		
p_{SR} –	probability of "driving rain"	(rain combined with wind)	[-]
b_W –	exponent of regression	(NDF → μ=0.446, σ =0.163)	[-]

Weather function, therefore, depends on 3 parameters – probability of driving rain, time of wetness and time of exposure. According to eq. (4), it is obvious that the maximum depth of carbonation takes place in case of minimum amount of precipitation (minimum number of rainy days per year) and if interior structural elements are treated (minimum probability of driving rain). It is due to the fact that a rain event will lead to saturation of the concrete surface which will, at least temporarily, prevent a further carbonation progress since the pores are widely filled with water.

Based on data obtained from Belgrade weather station, it is estimated that the average number of rainy days per year, for reference period of 50 years is 67, with standard deviation of 10 days. Varying the value for ToW within these limits (67±10), practically negligible

differences in values of weather function are obtained. The differences in the weather function and hence, in the carbonation depth, are up to 7.5%.

Probability of driving rain, p_{SR}, is defined by Model Code [4] as "the average distribution of the wind direction during rain events". In general, p_{SR} is evaluated as ratio between sum of days during one year with wind in considered direction, while at the same day a "decisive" rain event is taking place, and sum of days during one year with "decisive" rain events [13]. Therefore, for elements sheltered from rain (interior) p_{SR} =0 while for horizontal elements p_{SR} =1. If vertical element treated, p_{SR} can take the value between 0 and 1 depending of exposure conditions determined by mean distribution of wind direction during "decisive" rain event and by structure geometry. This parameter p_{SR} cannot be determined based on the available data from weather station, but the impact of varying the value of p_{SR} on weather function, with adopted constant value ToW=67, should be obviously seen on figure 1.

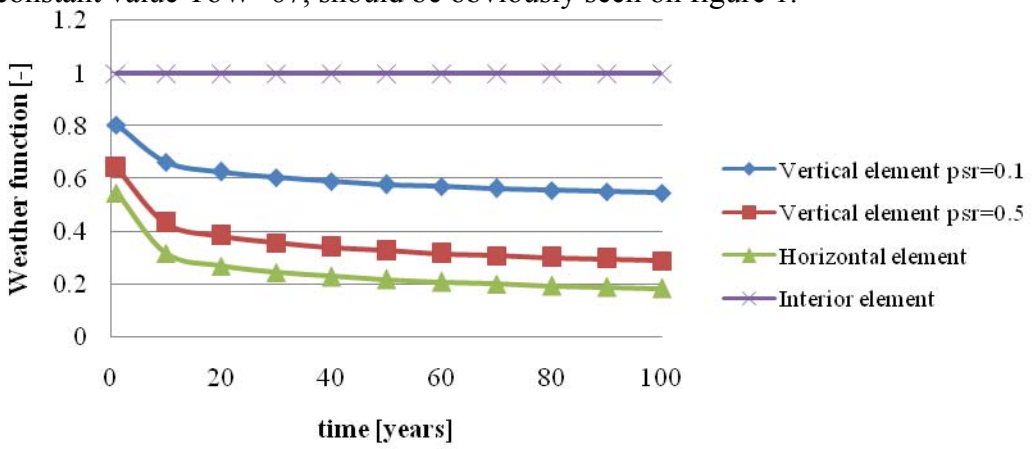

Figure 1: Weather function for different structural elements

Minimum values for weather function, W(t), are obtained for horizontal structural elements considering that these elements are directly exposed to precipitations which delay the carbonation process. Carbonation is far more important for vertical structural elements such as columns, chimneys, etc. where the value of the weather function, and therefore the depth of carbonation, may be even 3 times greater than for horizontal element, fig. 1.

2.5 Inverse Carbonation Resistance, $R_{ACC,0}^{-1}$

Carbonation resistance of concrete is determined by accelerated carbonation tests (ACC-test) in which laboratory pre-stored concrete specimens are tested under defined conditions at a reference time t_0 [4]. However, doing the ACC test implies adequate equipment which, currently, none of the institutions in our country possess (!). In these cases, when no test data is available, it is suggested by Model Code [4] that data from literature can be used to quantify orientation value of $R_{ACC,0}^{-1}$. Yet, offered database is relatively small, due to the fact that there is no available data for all the concrete mixtures. In general, it is difficult to supply literature data for wide range of cement types and water/cement ratios which are commonly used in the construction industry. There is also the inevitable question of reliability of suggested literature data- number of specimens, laboratory and staff competence, etc. When (finally), one way or another, $R_{ACC,0}^{-1}$ is determined, value of inverse carbonation resistance

under "natural carbonation" conditions, $R_{ACC,0}^{-1}$ is calculated according to the following equation (5):

$$R_{NAC,0}^{-1} = k_t \cdot R_{AAC,0}^{-1} + \varepsilon_t \quad (5)$$

,where k_t is the regression parameter which considers the influence of test method on the ACC-test ($\mu = 1{,}25$, $\sigma = 0{,}35$) and ε_t is the error term considering inaccuracies which occur conditionally when using the ACC test method [$(mm^2/year)/(kg/m^3)$] ($\mu = 315{,}5$ $\sigma = 48$).

Obviously, inverse carbonation resistance defines the quality of concrete regarding its transport characteristics and permeability, i.e. diffusion coefficient of CO_2, which depends on type of cement and w/c ratio. Hence, over this parameter direct impact on design of concrete cover could be achieved, primarily by choice of adequate cement type. According to some studies [10, 11, 14, 15, 16], it is evident that depending of chosen cement mixture, $R_{ACC,0}^{-1}$ differs by an order of magnitude! But, it is also evident that there are different conclusions in above mentioned literature about the influence of supplementary cementing materials (fly ash, silica fume, blast furnace slag etc.) on the value of $R_{ACC,0}^{-1}$. Therefore, a detailed analysis of literature data and conduction of own experimental investigation is proposed in order to secure the proper estimation of inverse carbonation resistance. This proposal relies on the fact that utilization of cement with supplements is far more often than utilization of ordinary Portland cement in national construction industry.

Within the same cement type, varying the w/c ratio in range between 0.55 and 0.4 (read: from C20/25 to C35/45, commonly used) causes the change in value of $R_{ACC,0}^{-1}$ by 3 to 5 times which affects the carbonation depth up to 65%.

2.6 Discussion

According to the data obtained from different sources such as Belgrade weather station (RH, ToW) and literature (C_S, $R_{ACC,0}^{-1}$), author's knowledge and experience (t_c), the actual impact of each parameter on the carbonation depth in local environmental conditions (Belgrade, Serbia) was estimated. Results of this analysis are summarized in table 1. Five parameters necessary for determination of carbonation depth, according to equation 3, have been divided into two groups. In the first group parameters depend on environmental factors – relative humidity, concentration of CO_2, number of rainy and windy days. Although some of them greatly affect the carbonation depth (table 1), the designer can not influence on their values. The main issue for C_S parameter is precise measuring or estimating the real value of CO_2 concentration in the surrounding area of certain structure. In addition, it has to be noticed that the value of the carbonation depth shows great differences (up to 78%), depending on whether the structural element is interior, vertical, or horizontal. Obviously, the impact of rainy days per year in analyzed environment is minimal (up to 7.5 %). Therefore, this parameter can be adopted as constant based on yearly average values and thus considerably simplifying the calculation procedure.

Table 1. The influence of each parameter on the carbonation depth

	Parameters imposed by the environmental conditions						Paremeters controled by the designer					
parameter	environment function	environmental impact	weather function				inverse carbonation resistance					execution transfer
	k_e [-]	C_S [kg/m^3]	W (t)				$R_{ACC,0}^{-1}$ [(mm^2/year)/(kg/m^3)]					k_c [-]
				p_{sr} [-]			type of cement					
				structural el.			CEM I, II, III + SCM (*)					
dependent on factor	RH [%]	CO_2 conc. [ppm]	ToWx365	interior	vertical	horizontal	CEM I 42.5R	CEM I 42.5R + 22% FA	CEM I 42.5R + 5% SF	CEM III/B 42.5	w/c [-]	t_c [days]
varying range of factor	62-73	380-3000	57-77	0	0-1	1					0.4-0.55	2-3
varying range of parameter	1.07-0.76	0.00062-0.00489	(**)	(***)			3091	2050	###	13970	978-3091	1.43-1.27
			0.6-0.56	1	1-0.22	0.2						
impact on the carbonation depth [%]	**41**	**181**	**7.5**	**0**	**<0-78**	**<78**	**0**	**<17**	**>28**	**>106**	**65**	**12**

(*) supplementary cementing materials

(**) for p_{sr} adopted value 0.1

(***) for ToW adopted value 67

On the other hand, the parameters which can be changed and controlled by the designer are carbonation resistance and the curing period of concrete. By choosing the proper type of cement and/or water to cement ratio it is possible to increase carbonation resistance of concrete even by 2 or 3 times. However, that decision does not concern only durability design, but also the ultimate limit state design and the estimation of environmental impact (throughout the amount of cement production-lifecycle analysis-LCA). These parameters are crucial in understanding that design service life is not ensured only by increasing the concrete cover, but with proper concrete quality.

In general, for RC structures in analyzed local conditions some suggestions can be made:

- the environmental function, k_e, is of great importance, depending on reference period and the type of data used for determination the average value of RH
- the value of C_S is constant and should be taken as double value of global concentration - 700 ppm, e.c. 0.001141kg/m^3
- the value for ToW can be adopted as constant equal to 67; the value for p_{SR} have to be calculated for each of analyzed element of structure based on wind direction during rain event
- there is no suggestion about the value of $R_{ACC,0}^{-1}$; obtaining the value from ACC tests is the best option; the values given in literature have to be analyzed before being adopted
- the value for curing days can be adopted as 2, which give the value for execution function of 2.03.

Based on this examination and explanation in chapter 1, it is obvious that governing parameters are $R_{ACC,0}^{-1}$, k_e and p_{SR} and, if partial factor method is used as verification method of service life design, adequate safety factors should be added to them. Investigation on determing the safety factors will be analized in details in future works.

3. CONCLUSION

According to the new Model Code, the durability design achieved comparable level of reliability as load design based on probabilistic approach. The equation of carbonation model

tends to be universal and to include all differences in environmental conditions and material properties of concrete on a global level. At the same time, the probabilistic approach, which demands a wide range of databases and their statistical analysis, makes it too complicated for practical use. Analyzing the influence of each parameter from carbonation model and having in mind local conditions, it can be concluded that statistical distribution, and even characteristic values suggested by Model Code, can be replaced by approximate, mean values for majority of parameters. More important than methodology of use databases and calculating the reference values, is a detailed analysis of exposure conditions of a reinforced structural element or a reinforced concrete structure in general. In contrast to traditional approach where durability was achieved only by increasing the concrete cover, in modern code design is outlined the great impact of carbonation resistance on durability, which is assured by proper design of concrete mixture, correct choice of component materials and appropriate curing period of concrete.

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