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Self-terminated carbonation model as an useful support for durable concrete structure designing

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Abstract. The paper concerns concrete carbonation, the phenomena that occurs in every type of climate, especially in urban-industrial areas. In European Standards, including Eurocode (EC) for concrete structures the demanded durability of construction located in the conditions of the carbonation threat is mainly assured by the selection of suitable thickness of reinforcement cover. According to EC0 and EC2, the thickness of the cover in the particular class of exposure depends on the structural class/category and concrete compressive strength class which is determined by cement content and water-cement ratio (thus the quantitative composition) but it is not differentiated for various cements, nor additives (i.e., qualitative composition), nor technological types of concrete. As a consequence the selected thickness of concrete cover is in fact a far estimation - sometimes too exaggerated (too safe or too risky).

The paper presents the elaborated "self-terminated carbonation model" that includes abovementioned factors and enables to indicate the maximal possible depth of carbonation. This is possible because presented model is a hyperbolic function of carbonation depth in time (the other models published in the literature use the parabolic function that theoretically assume the infinite increase of carbonation depth value). The paper discusses the presented model in comparison to other models published in the literature, moreover it contains the algorithm of concrete cover design with use of the model as well as an example of calculation of the cover thickness.

Keywords: concrete; carbonation; self-terminated carbonation model; concrete cover design; durability

1. Introduction

The durability is one of the important determinants of building material sustainability as well as sustainability of the structure. Sustainable development of civil engineering demands from science taking up the new challenges in terms of the theory, methods and tools that enable to create not only environmentally friendly and energy efficient but also durable design and material-technological solutions. The durability of reinforced concrete structures exposed to environment depends on the ability of both - concrete and reinforcement - to resist the environmental factors. The most common cause of the reinforced concrete damage is the corrosion of steel resulting from not providing the efficient protection by the concrete cover. The protective abilities of concrete cover deteriorate with time due to the synergistic action of a number of physical and chemical factors. One of the most destructive factors apart from climatic phenomena (including frost or chemical aggression of e.g., chlorides or other aggressive agents causing corrosion of steel or concrete) is decreasing of pH value due to the activity of atmospheric carbon dioxide. Providing the durability of reinforced concrete structure working under certain environment conditions depends on providing proper (1) ***durability of concrete***, (2) proper ***thickness of the concrete cover***, as well as taking into consideration (during designing) serviceability limit states in terms of cracks, namely (3) calculating ***crack width*** which shall not exceed the Eurocodes limits (EN 1991 Eurocode: *Basis of structural design* - "EC0" and EN 1992 Eurocode 2: *Design of concrete structures* - "EC2"). Concrete elements and concrete structures should meet the design requirements established for the expected service life without significantly reducing the serviceability or incurring excessive and unforeseen maintenance costs.

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2. Shaping the durability according to standard requirements

The Principles of **material shaping of concrete durability** adopted in Europe, given in general European standard EN 206 (EN 206: *Concrete. Specification, performance, production and conformity*) and in the National Complements in relation to the local operating conditions of the structure (e.g., in Polish Complement PN-B-06265:2004).

From the point of view of the carbonation threat, principles and requirements are different for the four classes of concrete exposure (XC1÷XC4). The criterion of assigning to the particular exposure class is concrete cover humidity (see Table 1).

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Table 3 Recommendations for the use of cement by carbonation exposure class acc. to Polish National Complements to EN 206 (“+”– recommended, “NR”– not recommended)

Cement				Exposure Class				Prestressed concrete
				XC1	XC2	XC3	XC4	
CEM I				+	+	+	+	+
CEM II	A/B	S		+	+	+	+	+
	A	D		+	+	+	+	+
	A/B	P/Q		+	+	+	+	NR
	A/B	V		+	+	+	+	+
	A	W		+	+	+	+	NR
	B			+	+	NR	NR	NR
	A	L		+	+	+	+	+
	B			+	+	NR	NR	NR
	A	LL		+	+	+	+	+
	B			+	+	NR	NR	+
	A	M	S-D;S-LL;D-LL, S-P;S-V; D-P;D-V; P-V;P-L;V-LL	+	+	+	+	+
	B		S-D, S-V;D-V;P-V	+	+	+	+	+
			S-P;D-P	+	+	+	+	NR
			S-LL;D-LL;P-LL;V-LL	+	+	+	NR	+
CEM III	A/B			+	+	+	+	+
	C			+	+	NR	NR	NR
CEM IV	A			+	+	+	+	NR
	B			+	+	NR	NR	NR
CEM V	A			+	+	+	+	NR
	B			+	+	NR	NR	NR

Table 1 Environmental conditions corresponding with carbonation exposure classes according to EN 206

Exposure class	Environment
XC1	Dry or permanently wet, e.g., the interior of buildings or concrete permanently under water
XC2	Wet, rarely dry, e.g., foundation
XC3	Medium moist, e.g., the interior of high RH or exterior surfaces sheltered from the rain
XC4	Cyclic wet and dry e.g., the zone of water flow in the natural water areas or fluctuations in water level in reservoirs

Table 2 Requirements for concrete by carbonation exposure class according to EN 206

Requirement	Exposure class			
	XC1	XC2	XC3	XC4
Maximal value of w/c	0.65	0.60	0.55	0.50
Minimal concrete class	C20/25	C25/30	C30/37	C30/37
Minimal cement content, kg/m^3	260	280	280	300

For each exposure class there are formulated requirements in terms of water-cement ratio, concrete class and minimal content of cement (Table 2). According to standard EN 206 fulfilling these requirements ensures the durability of concrete for 50 years. Moreover, in Polish National Complements are given recommendations for the use of particular cements in the conditions of carbonation exposure class (Table 3).

The requirements in terms of the minimal **thickness of the concrete cover** due to durability formulated in Eurocode 2 (EC2) are different in case of reinforced concrete structures and prestressed concrete structures; also they are different for each type (category) of the structure defined in Eurocode 0 (EC0) and exposure class defined in the standard EN 206.

Due to EC0 and EC2 recommendations, when determining the structural class the exposure class XC specifics is taken into account. The structural class recommended by EC2 for the “common” structures designed for service life of 50 years is S4. If the service life of the structure is 100 years, then structural class is to be increased by 2, while in case of concrete strength class higher than C30/37 or in case of the slab elements or in situation where the “concrete special quality control” is required - structural class may be reduced by 1.

In EC0 there are defined 5 categories of design working

Design Working Life, yrs		Example of structure	Structural class*
1	< 10	Temporary structures	S1
2	10÷25	Removable part of s tructures	S2
3	15÷30	Agricultural structur es, etc.	S3
4	50	Buildings and other common structures	S4
5	100	Monumental build., bridges and other e ng. structures	S5
?	>100	Special structures	S6

Correction of structural class S4 according to:				
Exposure class	Concrete class	Slab elements	Special quality control	Service life >100 years
XC1	If ≥ C30/37 then S4 - 1 = S3	S4 - 1 = S3	S4 - 1 = S3	S4 + 2 = S6
XC2 XC3	If ≥ C35/45 then S4 - 1 = S3			
XC4	If ≥ C40/50 then S4 - 1 = S3			

*basis for determining minimal concrete cover thickness (see Table 4)

Fig. 1 Determining the structural class according to Eurocode EC0 and EC2 and the specific requirements for concrete exposure class XC given in standard EN 206

Table 4 Minimal thickness of concrete cover ($c_{min,dur}$, mm) required in case of reinforced concretes threatened by carbonation (R- reinforced, P- prestressed structure)

Structural class	Minimal concrete cover thickness $c_{min,dur}$ for the exposure class, mm					
	XC1		XC2 and XC3		XC4	
	Type of the structure					
	R	P	R	P	R	P
S1	10	15	10	20	15	25
S2	10	15	15	25	20	30
S3	10	20	20	30	25	35
S4	15	25	25	35	30	40
S5	20	30	30	40	35	45
S6	25	35	35	45	40	50

Table 5 Recommended limit value of crack width (w_{max}, mm) in case of reinforced concretes threatened by carbonation according to Eurocode EC2

Type of reinforcement and the conditions of occurrence of the actions	$w_{max,}$ mm for exposure class	
	XC1	XC1
Elements prestressed by tendons with bond Frequent combination of actions	0.2	0.2
Reinforced concrete elements, elements prestressed by tendons without bond / Quasi-permanent combination of actions	0.4	0.4

*Provided that they meet the requirements of decompression (i.e., each tendon is covered by a layer of compressed concr ete of thickness of at least 25 mm)

life (DWL), while in EC2 there are specified 6 structural classes. The record in EC2 about the need to increase the structural class S4 by 2 in case of assumption of a 100-year period of use leads to structural class S6 that refers to the 100 years of use. However, the same period of use is given in EC0 in relation to the category 5. It seems logical to assume that the record about the need to increase structural class S4 by 2 (i.e., to S6), should apply only to the case of the structure of the required service life of **over** 100 years, although this is not the case described in EC0.

Knowing the structural class determined according to Eurocodes EC0 and EC2 (Fig. 1) and specific requirements for concrete exposure class XC given in standard EN 206 (Table 2), it is possible to determine the minimal thickness of concrete cover ($c_{min,dur}$, mm) required in case of reinforced concretes located in the environment corresponding to the exposure class XC (Table 4).

The limit value of crack width (w_{max}, mm) calculated according to EC2 due to the durability of reinforcement of concrete threatened by carbonation depends on the type of reinforcement as well as the conditions of the occurrence of the variable actions (Table 5). Taking into consideration above it can be concluded that according to Eurocodes EC0 and EC2 the thickness of the cover in the particular class of exposure depends on the structural class/category and concrete compressive strength class which is determined by cement content and water-cement ratio (thus the quantitative composition) but it is not differentiated for various cements, nor additives (i.e., qualitative composition), nor technological types of concrete. As a consequence, the selected thickness of concrete cover is in fact a far estimation - sometimes too exaggerated (too safe/too risky).

3. Research significance

This paper contains author's own (Woyciechowski 2013, Czarnecki and Woyciechowski 2012, 2013, 2015, 2016) mathematical model of carbonation. The model defines the carbonation as the process of limited possible range into the concrete and is described by hyperbolic function of time. In the following paragraphs one will find the proposal of use of the model as a tool for determining the minimal thickness of the concrete cover, ensuring the durability of reinforced concrete structure due to the risk of carbonation. There is also given a practical algorithm of elaborating of the model and using it to determine the minimum cover due to carbonation.

The presented model of carbonation progress is different from the traditional models described by parabolic functions that were published worldwide so far (for details see paragraph 4), but it was verified in a wide range of material variables, technological variables as well as environmental variables published in the earlier works of the authors. Meanwhile the given algorithm enables optimal choice of the concrete cover thickness, which minimizes the uncertainty occurring during designing the reinforced concrete structures according to the simplified approach discussed in the first part of this paper.

4. Carbonation models

4.1 Traditional approach to mathematical model of carbonation

Research on the development of universal models of carbonation, describing its changes in time and taking into account different material and technological variables, has been conducted for many years in various research centers (Bary and Sellier 2004, Burkan *et al.* 2004, Hossain *et al.* 2005, Ishida, Maekawa and Soltani 2004, Maekawa and Ishida 2002, Loo *et al.* 1994, Masuda and Tanano 1991, Monteiro *et al.* 2012, Steffens *et al.* 2002, Papadakis 1991, Muntean 2009, Chuanqing Fu 2015, Medeiros-Junior 2015). In mathematical modeling of carbonation a key issue is to determine the intensity of carbon dioxide flow through concrete. The starting point is the first Fick's law, which allows to describe the diffusion process under a constant density of the diffusion flux. Final result of carbonation modeling is power function of carbonation depth in time, expressed in the form

$$x = \sqrt{\frac{2D\varphi_{ext}}{a}} \cdot \sqrt{t} \tag{1}$$

where: x - depth of carbonation; D - diffusion coefficient; φ_{ext}- external concentration of CO_2; t -time of carbonation; a - coefficient determining the amount of CO_2 bound in the way of carbonation by unit volume of concrete in kg/m^3, calculated acc. to the CEB Bulletin 238 (1997) as: a=0,75·C·[CaO]·αH·(M_{CO2}/M_{CaO}) (C - content of cement in concrete, kg/m^3; [CaO] - CaO content in the cement composition; αH - degree of hydration of cement; M_{CO2}, M_{CaO} - molar masses). In practice, the most widely used model is simplified. It relates to an average constant RH and carbon dioxide concentration in the environment and can be expressed in the form

$$x = A \cdot t^{0.5} + B \tag{2}$$

where: A is a constant depending on the diffusion coefficient, the ability of concrete to bind CO_2 and CO_2 concentration in the air, whereas B is an empirical factor accounting the initiation period of carbonation. This model is used by most researchers, for example Bary and Sellier (2004), Burkan *et al.* (2004), Hossain *et al.* (2005), Ishida, Maekawa and Soltani (2004), Maekawa and Ishida (2002), Loo *et al.* (1994), Masuda and Tanano (1991), Monteiro *et al.* (2012), Steffens *et al.* (2002), Papadakis (1991) or Muntean (2009) as a basic model that determines the depth of carbonation, after the time of exposure, *t*.

4.2 Model of carbonation as the finite process

The abovementioned models treat the phenomenon of carbonation as process occurring due to the exposure in environment containing carbon dioxide unlimited in concrete space and unlimited in time. It is assumed that the end of carbonation is related only to the exhaustion of reagents available in the system, including mainly $Ca(OH)_2$ and in the further horizon other hydrates. However, an important issue is the accessibility of CO_2 into the system, especially, in the deeper layers of concrete. Diffusion of CO_2 resulting from the concentration difference in the way from the surface into the concrete depends not only on the concentration gradient but also on the concrete microstructure. The described models based on the first Fick`s law assume that the medium in which diffusion takes place will not change over time, which allows the reception of a constant diffusion flux in the equation (1). This is a significant simplification of carbonation process description, which does not take into account a number of additional factors, such as changes in diffusivity as a function of humidity, changes in atmospheric concentrations of CO_2 in climatic year, participation in the carbonation of CSH phase and residuals of non-hydrated cement, qualitative and quantitative characteristics of the material composition of concrete (w/c, type of cement, additives, admixtures, aggregates size and content), technological and environmental factors (curing, temperature, state of stress) and, first of all, diffusivity changes resulting from changes in time of the concrete microstructure. The latter effect, resulting from the saturation of the pores with carbonation products, limits the possibility of a direct description of a process based on Fick's law. The result of carbonation is a decrease in porosity, in particular capillarity that takes place in addition to the occurrence of carbonation shrinkage, thus reducing the permeability of the concrete and therefore the possibility of diffusion of gases in concrete. This nature of the phenomenon was mentioned for the first time by Bakker in 1988, (Bakker 1988) and later by Hergenröder (1992), Nilsson (1996) and Fagerlund (1997). Such approach to the carbonation phenomenon was further developed in the Department of Building Materials Engineering on Warsaw University of Technology under the guidance of Czarnecki and results were widely published (Czarnecki and Więcławski 2003, Woyciechowski 2013, Czarnacki and Woyciechowski 2012, 2013, 2015, 2016, 2012, Czarnecki

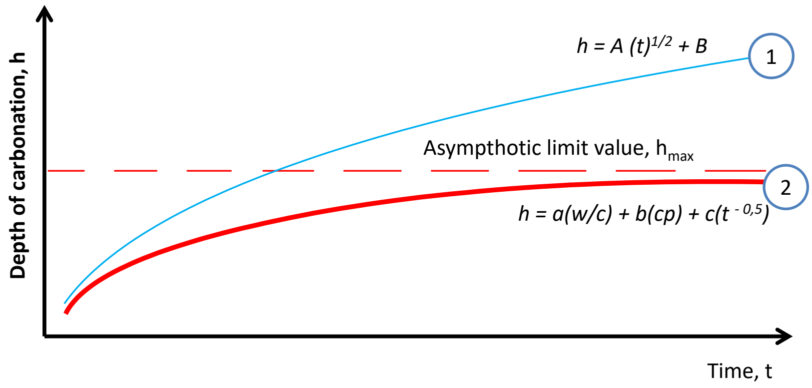

Fig. 2 "Traditional" power (1) and hyperbolic (2) models of carbonation phenomena

and Sokołowska 2015).

Abovementioned works conclude that concrete carbonation in urban-industrial conditions can be described with a hyperbolic function of carbonation depth in time (reciprocal square root of time), which has asymptotic value parallel to time axis. This asymptote is a limit of carbonation depth. Traditional and hyperbolic models of carbonation are shown on Fig. 2.

The hyperbolic carbonation model is expressed in the form

$$h = a(w/c) + b(cp) + c(t^{-0.5}) \tag{3}$$

where: h - depth of carbonation, mm, w/c - water-cement ratio, cp - early curing period, days, t - time of exposition, days, a, b, c - coefficients describing relevance of influence of w/c ratio, early curing and exposition time on depth of carbonation. It was stated that parameters a, b, c depend mainly on binder, mineral additives and, especially, on CO_2 concentration. Similar models were elaborated for different concrete types, particularly with use of Portland cement and cement incorporating slag and fly ash.

SEM analysis shows different density of concrete structure in carbonated and non-carbonated zones. It was stated that all results are in accordance with hyperbolic model expressed in the form

$$h = f(t^{-0.5}) \tag{4}$$

regardless of binder composition, but various function characteristic coefficients were obtained for various cements. Determination of carbonation hyperbolic model allows to specify a maximum depth of carbonation and compare it with the thickness of reinforcement cover in the analyzed element. This allows to assume if there is a risk of corrosion due to the carbonation and to estimate the time when the carbonation front will reach the reinforcement, which can be considered as a time of corrosion initiation.

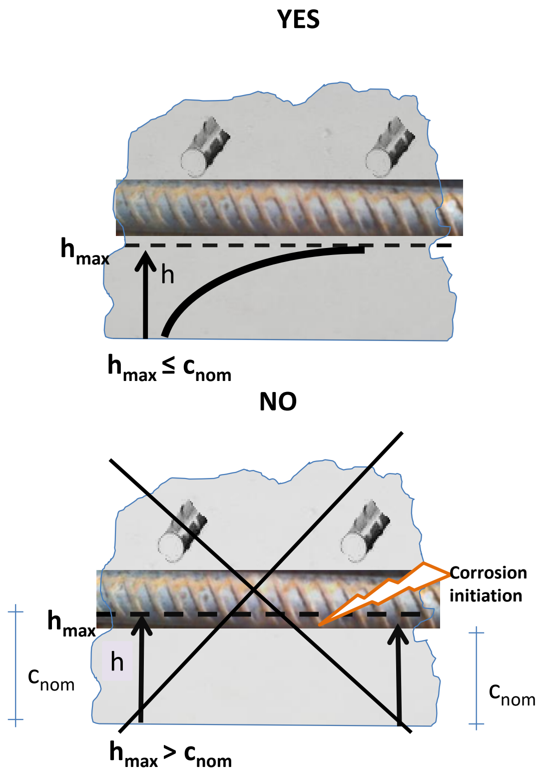

Fig. 3 Thickness of the reinforced concrete cover (c_{nom}) greater than maximal possible concrete carbonation depth (h_{max}) -no risk of reinforcement corrosion initiation (upper figure), smaller than maximal carbonation depth (h_{max}) -conditions for reinforcement corrosion initiation (lower figure)

5. Design of reinforcement concrete cover thickness using hyperbolic carbonation model

5.1 Assumptions

Determination of the proper concrete cover thickness due to durability of construction located in conditions of the carbonation threat includes determination of the exposure class (XC1÷XC4) according to EN 206 that describes the moisture condition of concrete in the environment with CO_2 and minimal concrete cover thickness according to rules given in Eurocode EC2 (EN 1992-1-1). The minimal values of concrete cover thickness given in the Eurocode, apart from exposure class, take into account only structural class (S1÷S6) and type of the reinforcement steel (mild steel, prestressed steel). The approach of using the carbonation model elaborated in the way of research (on the basis of collected data) and statistic curve-fitting for a particular

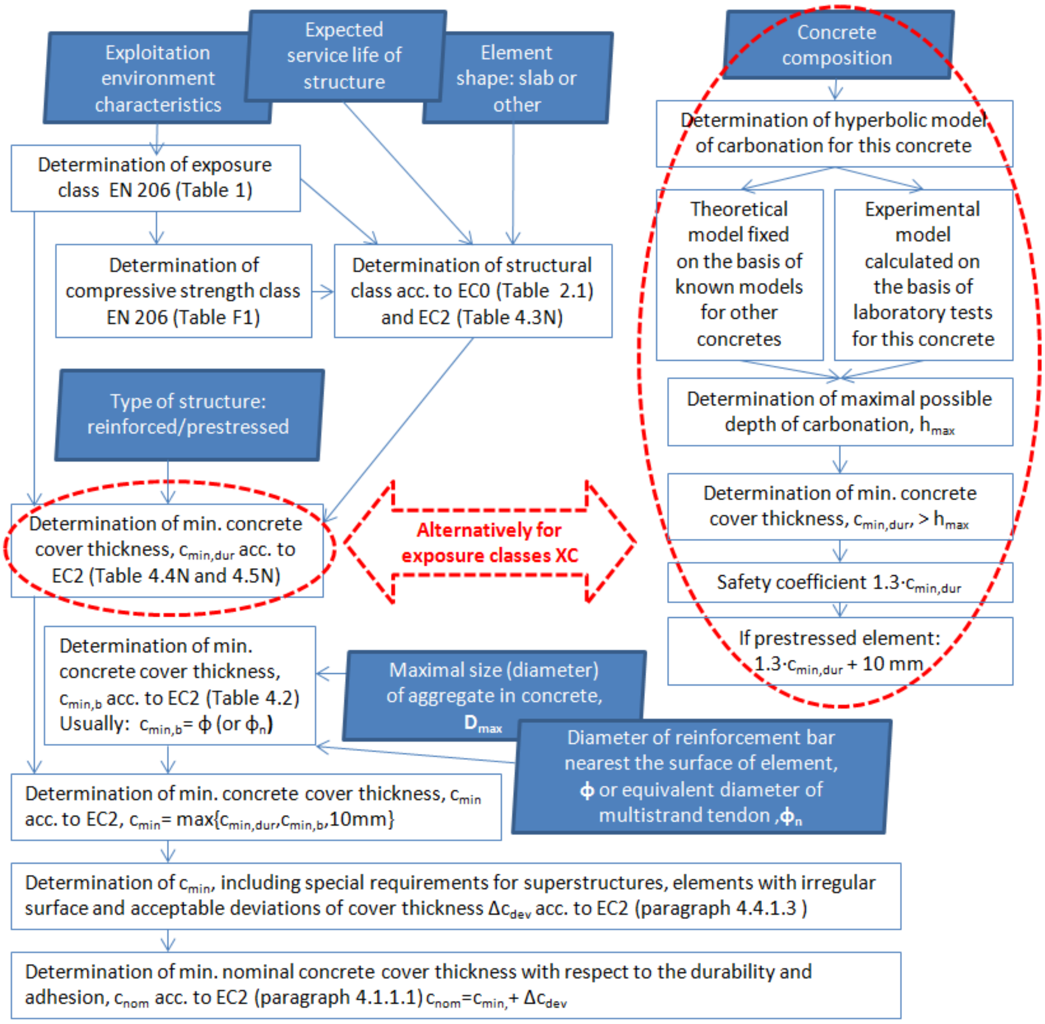

Fig. 4 Procedure of determination concrete cover thickness of the reinforcement with an option of hyperbolic carbonation model use

type of concrete designed for use in structure, enables to design the thickness of the concrete cover for the individual case on the basis of the actual protective abilities of particular concrete. The design should take into account the fact that if the process of carbonation is finite, adopting thickness of the reinforcement concrete cover greater than the maximum possible depth of carbonation of concrete (in the hyperbolic model the value of asymptote h_{max}) assures that the initiation of reinforcement corrosion does not arise in the structure (Fig. 3). However it is also possible to reduce the cover thickness to the depth of carbonation calculated for the particular DWL if the structure is not to be used for the longer time.

5.2 Procedure of determining the thickness of reinforcement concrete cover with option of hyperbolic carbonation model use

When designing the reinforced concrete element, on the stage of determination the concrete cover thickness due to durability as an alternative for the approach based on rules given in EC2 and EC0 (see paragraph 2), one can also apply an experimental-computational method for determining the minimum concrete cover thickness using the hyperbolic carbonation model (Fig. 4).

The value of $c_{min,dur}$ designated in the alternative way ("right path" of the diagram on Fig. 3) should be multiplied by a safety margin due to the uncertainty of estimation proceeded by this method. According to the authors, taking into consideration probabilistic evaluation of data obtained during the large-scale research on carbonation, the safety coefficient value of 1,3 is sufficient.

Elaborating of the hyperbolic carbonation model that can be used in the procedure presented on the Fig. 4 requires the adoption of the initial basic assumptions determining both the forecasting methodology and its results. These assumptions relate to the procedure in terms of determination the critical concrete pH value and in terms of choice of the method of determining a maximum depth of carbonation. Practically possible variants of the procedure are compared in the Table 6.

6. Example of calculation of the cover thickness for reinforced concrete element

6.1 Subject of the calculation: reinforced concrete

column -composition and characteristics of concrete

The presented below example of the calculation of concrete cover thickness was done for the reinforced concrete column of service life designed for **at least 50 years** in the following exposure environmental atmospheric conditions:

- relative humidity RH: up to 90%,
- ambient temperature: $+3^{\circ}C \div +40^{\circ}C$,
- natural CO_2 concentration: approx. 400 ppm.

The above environmental conditions according to standard EN 206 are adequate to **carbonation exposure class XC4** (see Table 1).

The control conditions of production and concrete works on site for the structure are set up as **normal conditions**.

The qualitative material composition of the concrete mix used to produce the analyzed reinforced column is as following:

- cement binder: Portland siliceous fly ash cement of class 32.5 and high early strength: CEM II/A-V 32.5 R,
- aggregate: natural aggregate (gravel) of fraction 0/16 mm, including river sand,
- water: tap water fulfilling the requirements of standard EN 1008,
- admixture: superplasticizer

The quantitative material composition of the concrete mix used to produce the analyzed reinforced column expressed per 1 m^3 is as following:

- cement - 365 kg,
- aggregate - 1927 kg,
- water - 155 dm^3,
- superplasticizer - 1,3% of cement mass (i.e., 4.75 kg).

Above gives composition enabled to obtain concrete of compressive strength class C30/37. The correctness of this composition was confirmed by laboratory tests performed on concrete specimens (cylinders of size 15/30 cm) cured

Table 6 Basic assumptions for determining carbonation model

1st Assumption: critical level of pH initiating reinforcement corrosion			
Variant	pH value (type of used indicator)	Analysis	
		Advantages and possibilities	Advantages and possibilities
1	8.3 (phenolphthalein)	• Test procedure described in standard EN 14630, • low coefficient of variance in test results	• the value is much lower than the real critical level of corrosion initialization • the value is a bit lower than the real critical level of corrosion initialization
2	9.6 (tymol- phenolphthalein)	• lower coefficient of variance in test results than in case of "phenolphthalein test (1)"	• the value is a bit lower than the real critical level of corrosion initialization
3	10.5 (thymolphthalein)	• Value is close to real critical level of corrosion initialization	• high coefficient of variance in test results
4	Wide range („Rainbow test")	• possibility of testing few levels of pH during one test	• difficulties during indicating the limits between colors corresponding with particular pH levels – not precise test
2nd Assumption: Method of determining time when carbonation reaches the reinforcement			
Variant	Method	Analysis	
		Advantages and possibilities	Advantages and possibilities
1	Elaborating of model based on results obtained for molded specimens of particular concrete in accelerated laboratory tests	• good estimation of carbonation depth, • test time: minimum 3 months	• requires preparation of the concrete specimens of composition as in the tested concrete structure
2	Elaborating of model based on results obtained for specimens taken from the structure in accelerated laboratory tests	• good estimation of carbonation depth, • test time: minimum 2 months	• unknown influence of carbonation rate change on the final result of test
3	Adopting the average carbonation rate on the basis of concrete composition and characteristics	• testing not required, which significantly reduces test time	• average carbonation rate value adopted from literature data can be erroneous
4	Measurements of carbonation depth in the structure and calculation of carbonation rate on the basis of construction age	• Test "in situ" enables taking into account the actual condition of structure when assessing carbonation rate	• calculations assume linearity of carbonation changes in time, which is erroneous; the shorter the time of carbonation occurring in concrete, the higher error value

Note: In practice, depending on the availability of data in a particular case, authors usually use:

- variant 1 of 1st assumption and variant 3 of 2nd assumption,
- variant 1 of 1st assumption and variant 1 of 2nd assumption,
- variant 3 of 1st assumption and variant 1 of 2nd assumption.

under suitable moisture conditions for 28 days: the average **compressive strength of concrete (f_{cm}) was 39.1 MPa**, while the lowest, minimal registered value of compressive strength ($f_{c,\min}$) was 35.3 MPa, which confirmed conformity with **class C30/37** requirements according to the standard EN 206.

6.2 Designing of cover thickness: Variant I - according to Eurocodes

The designing process presented in this variant (on the basis of EC0 and EC2) is proceeded according to "left path" of the algorithm presented on Fig. 3. This procedure depends on the structural class and DWL category and concrete strength class (it is not differentiated for various qualitative composition, nor technological types of concrete).

The first step of algorithm requires determination of the expected service life of structure i.e. analyzed element and the adequate structural class.

The second step is the analysis of the exploitation environment characteristics, including the carbonation threat, the shape of the reinforced element and quality control conditions and potential correction of the structural class in accordance to above-mentioned criteria.

The third step is determination of the type of reinforcement (whether the element is reinforced or prestressed) and on this basis - according to EC2 - determination of the minimal thickness of concrete cover ($c_{\min,dur}$, mm) required in case of reinforced concrete elements located in the environment corresponding to the particular exposure class XC. <u>In analyzed case:</u>

1. The service life of structure is designed for at least 50 years, which according to the Eurocodes (see Table 4) indicates the **structural class S4**.
2. According to the specific requirements for shape element, quality control conditions and concrete exposure class XC given in standard EN 206 (see Table 4) there is no need of additional correction of the structural class:
2.1 Since the analyzed reinforced concrete element is in the shape of column (not the slab) there is no need to make any correction of the structural class according to this criterion. The structural class remains S4.
2.2 Since the control conditions are set up as normal (no special quality control provided) there is no need to make any correction of the structural class according to this criterion. The structural class remains S4.
2.3 Since the carbonation exposure class is XC4 and compressive class of the concrete is C30/37 (i.e. lower than C40/50) there is no need to make any correction of the structural class according to this criterion. The structural class remains S4.
Conclusion: the **structural class is S4**.
3. According to requirements for the type of reinforcement and carbonation exposure class (see Table 5) as the minimal concrete cover of reinforcement in the analyzed reinforced (not prestressed) concrete column of structural class S4 exposed to carbonation exposure class XC4 is indicated thickness **$c_{\min,dur}$ of 30 mm**.

Final result: according to rules and requirements formulated in Eurocodes EC0 and EC2 and European standard EN 206 **the minimal concrete cover thickness of analyzed reinforced column is 30 mm**.

6.3 Calculation of cover thickness: Variant II - calculation with use of hyperbolic carbonation model

The calculation presented in this variant (done on the basis of hyperbolic carbonation model) is proceeded according to "right path" of the algorithm of determining the thickness of reinforcement concrete cover presented on Fig. 3. This procedure depends on the material composition of concrete and the self-terminated carbonation model elaborated on the basis of the results of laboratory tests of carbonation of concrete performed in the accelerated conditions.

The first step of algorithm requires determination of the material composition of the concrete for the particular class (see paragraph 6.1.).

The second step is preparation of the specimens for testing the compressive strength class of concrete (and determining that class) and for carbonation tests, the exposure of concrete specimens to the particular carbon dioxide concentration for the required time and in the meantime the measurements of carbonation depth after particular times of exposure (results of measurements are data for calculating the carbonation model). When testing in accordance with standard methods there are two accelerated testing procedures (EN 13295 - recommends 1% concentration of CO_2; draft of EN 12390-12 - 4% of CO_2) and testing period of respectively 90 or 70 days is sufficient for obtaining asymptote value considered as reliable.

The third step is calculation of the mathematical model describing the relation between the time of exposure to CO_2 and concrete carbonation depth according to the Eq. (4). and indicating the value of the model asymptote, which is a limit of carbonation depth ($h_{\max}$). This value is actually 10-15% higher than value obtained for the same concrete after many years of exposure to natural atmospheric conditions (400 ppm of CO_2). It means that $h_{\max}$ is a little bit excessive, however on a safe side.

The fourth step is determining the minimal concrete cover of reinforcement in the analyzed reinforced concrete element ($c_{\min,dur}$) - the value must be higher than the possible concrete carbonation depth ($h_{\max}$) determined from the carbonation model. The value should be multiplied by the safety coefficient of 1.3 (see paragraph 5.2) and adjusted to the accuracy of stabilization of reinforcement in the formwork. <u>In analyzed case:</u>

1. The material composition of the concrete mix used to produce the analyzed reinforced column expressed per 1 m^3 is as given in paragraph 6.1.
2. The average compressive strength of concrete (f_{cm}) was 39.1 MPa, while the lowest, minimal registered value of compressive strength ($f_{c,\min}$) was 35.3 MPa, which according to the standard EN 206 met requirements of **class C30/37**. The concrete specimens were exposed to **CO_2 at a concentration of 1% (10000 ppm) (RH 60%, T=20^{o}C) for 90 days** (accelerated

carbonation conditions).

3. Based on the measurements of carbonation depth after subsequent times of exposure to CO_2 at a concentration of 1% (10000 ppm) dome by authors, the carbonation hyperbolic model was calculated in the form as in Eq. (5). The model was calculated using multi-regression analysis:

$$h = 13.6 - 33.8 \cdot (t^{-0.5}) \quad (5)$$

According to above model, the asymptote of the function and at the same time the maximal depth of carbonation $\boldsymbol{h_{max}}$ **is 13.6 mm**.

4. The maximal depth of carbonation (h_{max}) multiplied by the a safety coefficient of 1.3 gives the value of minimal concrete cover thickness, $\boldsymbol{c_{min,dur}}$**=1.3·13.6=17.7 mm**. Taking into consideration that the accuracy of stabilization of reinforcement in the formwork, the minimal concrete cover thickness in analyzed reinforcement concrete element should be increased from 17.7 mm up to **20 mm.**

Final result: according to self-terminated hyperbolic carbonation model elaborated for the particular concrete (of composition given in paragraph 6.1) **the minimal concrete cover thickness of analyzed reinforced column is 20 mm**. This is 10 mm less than in case of Variant I (paragraph 6.2), where according to Eurocodes EC0 and EC2 and European standard EN 206 the minimal concrete cover thickness was indicated as 30 mm.

7. Conclusions

Presented example of designing the concrete cover thickness in reinforced element in two ways confirms that elaborating the precise and accurate mathematical models of concrete carbonation describing the increase of the carbonation depth in the concrete in time and application of such models for designing the reinforced structures in terms of ensuring the required durability is useful and reasonable. The example clearly showed that estimating of minimal concrete cover thickness in terms of carbonation threat on the basis of the Eurocodes EC0 and EC2 and European standard 206 is an overestimation and significantly increases the cost of whole structure.

However one should be sure about the correctness of the elaborated model. Authors hope that presented analysis of the “traditional” carbonation models in the context of their deficiencies in describing the phenomenon of carbonation, which actually is terminated phenomenon, will encourage others to use more correct models described by hyperbolic functions, as in case of given example.

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