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 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 only on the structure category and concrete strength class – it is not differentiated for various cements, nor additives, 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.

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

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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
cement 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 would 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.

2. SHAPING THE DURABILITY ACCORDING TO STANDARD REQUIREMENTS

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 (eg. 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).

<table>
<thead>
<tr>
<th>Exposure class</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>XC1</td>
<td>Dry or permanently wet, eg. the interior of buildings or concrete permanently under water</td>
</tr>
<tr>
<td>XC2</td>
<td>Wet, rarely dry, eg. foundation</td>
</tr>
<tr>
<td>XC3</td>
<td>Medium moist, eg. the interior of high RH or exterior surfaces sheltered from the rain</td>
</tr>
<tr>
<td>XC4</td>
<td>Cyclic wet and dry eg. the zone of water flow in the natural water areas or fluctuations in water level in reservoirs</td>
</tr>
</tbody>
</table>

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).
Table 2 Requirements for concrete by carbonation exposure class acc. to EN 206

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Exposure class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximal value of w/c</td>
<td>XC1  XC2  XC3  XC4</td>
</tr>
<tr>
<td>Minimal concrete class</td>
<td>C16/20 C16/20 C20/25 C25/30</td>
</tr>
<tr>
<td>Minimal cement content, kg/m³</td>
<td>260  280  280  300</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Cement</th>
<th>Exposure class</th>
<th>Prestressed concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEM I</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A/B S</td>
<td>+ + + + + +</td>
<td></td>
</tr>
<tr>
<td>A D</td>
<td>+ + + + + +</td>
<td></td>
</tr>
<tr>
<td>A/B P/Q</td>
<td>+ + + + + NR</td>
<td></td>
</tr>
<tr>
<td>A/B V</td>
<td>+ + + + + +</td>
<td></td>
</tr>
<tr>
<td>A W</td>
<td>+ + + + + NR</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>+ + NR NR NR</td>
<td></td>
</tr>
<tr>
<td>A L</td>
<td>+ + + + + +</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>+ + NR NR NR</td>
<td></td>
</tr>
<tr>
<td>A LL</td>
<td>+ + NR NR +</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>+ + NR NR +</td>
<td></td>
</tr>
<tr>
<td>CEM II</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A M</td>
<td>S-D;S-LL;D-LL, S-P;S-V;D-P;D-V;P-V;P-L;V-LL</td>
<td>+ + + + + +</td>
</tr>
<tr>
<td>B</td>
<td>S-D, S-V;D-V;P-V</td>
<td>+ + + + + +</td>
</tr>
<tr>
<td></td>
<td>S-P;D-P</td>
<td>+ + + + NR</td>
</tr>
<tr>
<td></td>
<td>S-LL;D-LL;P-LL;V-LL</td>
<td>+ + + NR +</td>
</tr>
<tr>
<td>CEM III</td>
<td>A/B</td>
<td>+ + + + + +</td>
</tr>
<tr>
<td>C</td>
<td>+ + NR NR NR</td>
<td></td>
</tr>
<tr>
<td>CEM IV</td>
<td>A</td>
<td>+ + + + + +</td>
</tr>
<tr>
<td>B</td>
<td>+ + NR NR NR</td>
<td></td>
</tr>
<tr>
<td>CEM V</td>
<td>A</td>
<td>+ + + + + +</td>
</tr>
<tr>
<td>B</td>
<td>+ + NR NR NR</td>
<td></td>
</tr>
</tbody>
</table>

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.

The analysis of the EC0 and EC2 indicates a certain inconsistency in records concerning the structural class. In EC0 there are defined 5 categories of structure, while in EC2 there are specified 6 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 S5. 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 (Table 4) 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 5).

Table 4 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>
<thead>
<tr>
<th>Service time, years</th>
<th>Example of structure</th>
<th>Structural class (category)*</th>
<th>Correction of structural class S4 according to:</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 10</td>
<td>Temporary structures</td>
<td>S1</td>
<td></td>
</tr>
<tr>
<td>10 ÷ 25</td>
<td>Removable part of structures</td>
<td>S2</td>
<td></td>
</tr>
<tr>
<td>15 ÷ 30</td>
<td>Agricultural structures, etc.</td>
<td>S3</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>Buildings and other common structures</td>
<td>S4</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>Monumental build., bridges and other eng. structures</td>
<td>S5</td>
<td></td>
</tr>
<tr>
<td>&gt; 100</td>
<td>Special structures</td>
<td>S6</td>
<td></td>
</tr>
</tbody>
</table>

*) basis for determining minimal concrete cover thickness (see Table 5)

Table 5 The minimal thickness of concrete cover (c_{min,dur}, mm) required in case of reinforced concretes threatened by carbonation

<table>
<thead>
<tr>
<th>Structural class</th>
<th>Minimal concrete cover thickness c_{min,dur} for the exposure class, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>XC1</td>
</tr>
<tr>
<td>Type of the structure</td>
<td>reinforced</td>
</tr>
<tr>
<td>S1</td>
<td>10</td>
</tr>
<tr>
<td>S2</td>
<td>10</td>
</tr>
<tr>
<td>S3</td>
<td>10</td>
</tr>
<tr>
<td>S4</td>
<td>15</td>
</tr>
<tr>
<td>S5</td>
<td>20</td>
</tr>
<tr>
<td>S6</td>
<td>25</td>
</tr>
</tbody>
</table>

The limit value of crack width (w_{max}, mm) calculated according to Eurocode 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 6).
Table 6 Recommended limit value of crack width ($w_{\text{max}}$, mm) in case of reinforced concretes threatened by carbonation according to Eurocode EC2

<table>
<thead>
<tr>
<th>Type of reinforcement and the conditions of occurrence of the actions</th>
<th>$w_{\text{max}}$ mm for exposure class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elements prestressed by tendons with bond</td>
<td></td>
</tr>
<tr>
<td>Frequent combination of actions</td>
<td>0,2</td>
</tr>
<tr>
<td>Reinforced concrete elements, elements prestressed by tendons without bond</td>
<td>0,4</td>
</tr>
<tr>
<td>Quasi-permanent combination of actions</td>
<td>0,3</td>
</tr>
</tbody>
</table>

*) provided that they meet the requirements of decompression (ie. each tendon is covered by a layer of compressed concrete of thickness of at least 25 mm)

Taking into consideration above it can be concluded that according to Eurocodes EC0 and EC2 the thickness of the cover in the particular exposure class depends only on the structural class/category and concrete strength class – it is not differentiated for various cements, nor additives, 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).

2. 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 3), 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.

3. CARBONATION MODELS

3.1 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, Ming Te Liang et al. 2002, Monteiro et al. 2012, Steffens et al. 2002, Papadakis 1991, Muntean 2009). 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:

\[ x = \sqrt{\frac{2D\varphi_{\text{ext}}}{a}} \cdot \sqrt{t} \]  

(1)

where: \( x \) – depth of carbonation; \( D \) – diffusion coefficient; \( \varphi_{\text{ext}} \) – external concentration of \( \text{CO}_2 \); \( t \) – time of carbonation; \( a \) – coefficient determining the amount of \( \text{CO}_2 \) bound in the way of carbonation by unit volume of concrete in \( \text{kg/m}^3 \), calculated acc. to the CEB Bulletin 238 (1997) as: \( a = 0.75 \cdot C \cdot \left[ \text{CaO} \right] \cdot \alpha_H \cdot \left( \frac{M_{\text{CO}_2}}{M_{\text{CaO}}} \right) \) (\( C \) – content of cement in concrete, \( \text{kg/m}^3 \); \( \left[ \text{CaO} \right] \) – \( \text{CaO} \) content in the cement composition; \( \alpha_H \) – degree of hydration of cement; \( M_{\text{CO}_2}, M_{\text{CaO}} \) – molar masses).

In practice, the most widely used model is greatly simplified. It relates to an average constant RH and carbon dioxide concentration in the environment and can be expressed in the form:

\[ x = A \cdot t^{1/2} + B \]  

(2)

where \( A \) is a constant depending on the diffusion coefficient, the ability of concrete to bind \( \text{CO}_2 \) and \( \text{CO}_2 \) 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), Ming Te Liang et al. (2002), Monteiro et al. (2012), Steffens et al. (2002), Papadakis (1991) or Muntean (2009) as a basic model that determines the depth of carbonation, \( x \) after the time of exposure, \( t \).

### 3.2 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 \( \text{Ca(OH)}_2 \) and in the further horizon other hydrates. However, an important issue is the accessibility of \( \text{CO}_2 \) into the system, especially, in the deeper layers of concrete. Diffusion of \( \text{CO}_2 \) 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\textsubscript{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 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. 1.

![Fig. 1 “Traditional” power (1) and hyperbolic (2) models of carbonation phenomena](image)

The hyperbolic carbonation model is expressed in the form:

\[ h = a(w/c) + b(cp) + c(t - 0.5) \quad (3) \]

where: \( h \) – depth of carbonation, mm, \( w/c \) – water-cement ratio, \( t_{ec} \) – early curing time, days, \( t \) – time of exposition, years, \( a, b, c \) – 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) mainly depend on binder properties, presence of mineral additives and, especially, on CO\textsubscript{2} concentration. Similar models were elaborated for different types of concrete, 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:

\[ h = f(t^{\sigma}) \]  

(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.

4. DESIGN OF REINFORCEMENT CONCRETE COVER THICKNESS USING HYPERBOLIC CARBONATION MODEL

4.1 Assumptions

Determination of the proper thickness of concrete cover due to the durability of construction located in the conditions of the carbonation threat includes determination of the XC 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, prestressing steel). The approach of using the carbonation model designated in the way of research for a particular 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 \(h_{\text{max}}\)) assures that the initiation of reinforcement corrosion does not arise in the structure (Fig. 2).

Fig. 2 Thickness of the reinforced concrete cover \(c_{\text{nom}}\) greater than maximal possible concrete carbonation depth \(h_{\text{max}}\) – no risk of reinforcement corrosion initiation (left), smaller than maximal carbonation depth \(h_{\text{max}}\) – conditions for reinforcement corrosion initiation (right)
4.2 Algorithm 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 algorithm 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. 3). The value of $c_{\text{min,dur}}$ 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 a safety coefficient of 1,3 is sufficient.

![Fig. 3 Algorithm of determination concrete cover thickness of the reinforcement with an option of hyperbolic carbonation model use](image-url)
Elaborating of the hyperbolic carbonation model that can be used in the algorithm the presented on the Fig. 3 requires the adoption of the initial basic assumptions determining both the forecasting methodology and its results. These assumptions relate to procedure in respect of:
- determination the critical level of pH initiating reinforcement corrosion,
- choice of the method of determining a maximum depth of carbonation.

Practically possible variants of the procedure are compared in the Table 7.

### Table 7 Basic assumptions for determining carbonation model

<table>
<thead>
<tr>
<th>pH value (type of used indicator)</th>
<th>Analysis</th>
<th>Disadvantages and risk</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1st Assumption: critical level of pH initiating reinforcement corrosion</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 8,3 (phenolphthalein)</td>
<td>• Test procedure described in standard EN 14630, low coefficient of variance in test results</td>
<td>• the value is much lower than the real critical level of corrosion initialization</td>
</tr>
<tr>
<td>2 9,6 (tymol- phenolphthalein)</td>
<td>• lower coefficient of variance in test results than in case of &quot;phenolphthalein test (1)&quot;</td>
<td>• the value is a bit lower than the real critical level of corrosion initialization</td>
</tr>
<tr>
<td>3 10,5 (thymolphthalein)</td>
<td>• the value is close to the real critical lever of corrosion initialization</td>
<td>• high coefficient of variance in test results</td>
</tr>
<tr>
<td>4 Wide range („Rainbow test”)</td>
<td>• possibility of testing few levels of pH during one test</td>
<td>• difficulties during indicating the limits between particular colors corresponding with particular pH levels – test is not precise</td>
</tr>
</tbody>
</table>

| **2nd Assumption: Method of determining time when carbonation reaches the reinforcement** |
| Method                                                                                         | Analysis                                                                 | Disadvantages and risk                                                                 |
| 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 the 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 |
In practice, depending on the availability of data in a particular case, authors usually use variant “1” and assumptions set “I” or variant “1” or “3” and assumptions set “II.

5. EXAMPLE OF CALCULATION OF THE COVER THICKNESS FOR REINFORCED CONCRETE ELEMENT

5.1 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 °C ÷ +40°С,
- natural CO₂ concentration: c.a. 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 m³ is as following:
- cement – 365 kg,
- aggregate – 1927 kg,
- water – 155 dm³,
- superplasticizer – 1,3% of cement mass (i.e. 4,75 kg).

Above gives the water-cement ratio of value 0,42. According to Bolomey equation the above composition enables to obtain concrete of compressive strength class C25/30. The correctness of this composition was confirmed by laboratory tests performed on concrete specimens (cubes of size 15 cm) cured 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 C25/30 requirements according to the standard EN 206.
5.2 Designing of cover thickness: Variant I - according to Eurocodes

The designing process presented in this variant (done on the basis of Eurocodes EC0 and EC2) is proceeded according to “left path” of the algorithm of determining the thickness of reinforcement concrete cover presented on Fig. 3. This procedure depends only on the structural class/category and concrete strength class (it is not differentiated for various cements, nor additives, 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 \( c_{\text{min,\,dur}} \) mm required in case of reinforced concrete elements located in the environment corresponding to the particular exposure class XC.

In analyzed case:
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 condition (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 C25/30 (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 \( c_{\text{min,\,dur}} \) 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.
5.3 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 5.1.).

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 CO₂; draft of EN 12390-12 – 4% of CO₂) 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 CO₂ 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 CO₂). 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 a safety coefficient of 1.3 and adjusted to the accuracy of stabilization of reinforcement in the formwork.

In analyzed case:
1. The material composition of the concrete mix used to produce the analyzed reinforced column expressed per 1 m³ is as following: cement – 365 kg, aggregate – 1927 kg, water – 155 dm³, super plasticizer – 1,3% of cement mass.
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 C25/30. The concrete specimens were exposed to CO₂ of concentration 1% (RH 60%, T = 20°C) for 90 days (accelerated carbonation conditions).
3. Based on the measurements of carbonation depth after subsequent times of exposure to CO₂ of concentration 1% the carbonation hyperbolic model was calculated in the form as follows:

\[ h = 13,6 - 33,8 \cdot (t^{-0.5}) \]  

(5)
According to above model, the asymptote of the function and at the same time the maximal depth of carbonation \( h_{\text{max}} \) is 13.6 mm.

4. The maximal depth of carbonation \( h_{\text{max}} \) multiplied by the a safety coefficient of 1.3 gives the value of minimal concrete cover thickness, \( c_{\text{min,dur}} = 17.7 \) mm. Taking into consideration that the accuracy of stabilization of reinforcement in the formwork, the minimal concrete cover thickness in analyzed reinforcement concrete element is \( 1.3 \cdot c_{\text{min,dur}} = 20 \) mm.

Final result: according to self-terminated hyperbolic carbonation model elaborated for the particular concrete on the basis of concrete material composition (cements, additives, technological types of concrete) and technical properties the minimal concrete cover thickness of analyzed reinforced column is 20 mm. This is 10 mm less than in case of variant I, where according to Eurocodes EC0 and EC2 and European standard EN 206 the minimal concrete cover thickness was indicated as 30 mm.

6. 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.

REFERENCES

EN 1991 Eurocode 0 : Basis of structural design.
EN 206 : Concrete. Specification, performance, production and conformity.


