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Limit values of accelerated carbonation resistance to meet EC2 durability requirements

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ABSTRACT

Although accelerated carbonation resistance has been extensively tested, there are no recommendations for the application of test results in codes of practice. The main objective of this study was to determine the limit values of accelerated carbonation resistance to satisfy the required service life of reinforced concrete structures with concrete covers as prescribed in EN 1992-1-1. The service life of 50 years was considered, as well as all carbonation exposure classes (from XC1 to XC4). A full probabilistic analysis was conducted using the fib-Bulletin 34 carbonation prediction model. Using the limit state function and a defined reliability index, the upper limits of the inverse effective carbonation resistance (R^{-1}_{ACC}) for all exposure classes and in a function of concrete cover depth were determined. The determined values of R^{-1}_{ACC} presented in this study represent the upper limit of the average value, as well as the maximum deviation of one sample in relation to this average value. Thus, a simple assessment of concrete quality is allowed in terms of carbonation resistance based on the accelerated carbonation depth measurements.

1 Introduction

Concrete is considered a building material with good durability properties. However, cases of insufficient service life are not uncommon [1]. The main reason for the deterioration of reinforced concrete (RC) structures is the corrosion of steel reinforcement. Reinforcement is protected by the surrounding concrete, which is a highly alkaline environment with a pH value of approximately 13 [2]. This ensures chemical protection of steel reinforcement with a thin oxide (passivation) layer. Carbonation-induced corrosion has been reported as a major durability problem in the urban environment, considering the large number of buildings that are exposed to a CO_2-rich environment [3]. Carbonation is the process by which CO_2 from the atmosphere enters concrete pores and reacts with the alkalis in the concrete matrix ($Ca(OH)_2$), lowering the pH of the concrete. When the pH value of concrete drops below 9, the chemical protection of the reinforcement will be degraded, and reinforcement corrosion can start [2].

The carbonation depth in natural conditions directly influences the concrete cover depth required for the desired service life [4]. Since natural carbonation is a very slow process, measured in years, carbonation resistance is usually determined based on accelerated carbonation tests. There are several ways to accelerate the carbonation process (increase in air pressure or temperature), but the most commonly used method is to increase the CO_2 concentration. This increase is done in specialized chambers, where the concentration of CO_2 can be up to a thousand times higher than in natural conditions. In different standards and technical recommendations, a great variety of CO_2 concentrations are prescribed, ranging from 1% to 50% [5]. It has been shown that under a CO_2 concentration of 2%, as proposed by the *fib*-Bulletin 34 [6], there will be no significant difference between the natural and accelerated carbonation processes [7,8]. There will be a difference in carbonation depth when comparing natural and accelerated carbonation, but the kinetics of the process will not change (there will be no increase in humidity and the formation of different compounds). This is important because *fib*-Bulletin 34 [6] allows the use of accelerated carbonation depth for the prediction of natural carbonation depth over time using the proposed prediction model.

Although accelerated carbonation resistance has been extensively tested, there are no recommendations for the application of test results in codes of practice, such as EN 1992-1-1 [9]. In current codes, the durability of concrete is ensured by a sufficient concrete cover and prescribed composition or compressive strength [10]. A concrete cover is defined for each exposure class to carbonation and service life duration. Also, the minimum concrete strength classes that can be used for certain exposure classes are defined. The prescribed composition (minimum amount of cement and maximum water-cement ratio) of concrete is only a recommendation in SRPS U.M1 206-1 [10]. Having in mind the increasing use of concrete with recycled and waste materials, pozzolanic cements, as well as the use of fillers that reduce the amount of cement in concrete, this recommendation is not adequate. Different concrete types,

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although belonging to the same strength classes, do not have the same durability properties, and vice versa [4]. Also, prescribing the minimum amount of cement is not in line with the agenda of reducing CO_2 emissions in the construction industry [11]. The cement industry causes approximately 7–10% of all anthropogenic origin CO_2 emissions [12], which impacts the environment and causes significant greenhouse gas emissions.

On the other hand, there is no carbonation resistance criteria defined in SRPS U.M1 206-1 [10], as defined for other durability related properties such as chloride ingress, freeze-thaw effect, and water permeability. Therefore, the limit values of characteristic parameters should be defined so that each concrete must satisfy these requirements during the accelerated testing in order to meet the requirements of the prescribed service life with the prescribed concrete covers.

2 Objectives and Methodology

Concrete carbonation resistance has already been the topic of many studies, but the use of test results to determine concrete cover depth according to EN 1992-1-1 [9] is still unknown. Therefore, the objective of this study was to determine the limit values of accelerated carbonation resistance to satisfy the required service life of RC structures for different exposure classes prescribed in EN 1992-1-1 [9]. The standard S4 structural class defined in EN 1992-1-1 [9] was considered corresponding to a service life of 50 years, as well as all exposure classes to carbonation (from XC1 to XC4).

In order to define the concrete resistance that corresponds to prescribe concrete cover, it is necessary to know the development of carbonation depth over time under natural exposure conditions. For that purpose, *fib*-Bulletin 34 [6] was used:

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

where, $x_c(t)$ is carbonation depth at the time t [mm], k_e is environmental function [-], k_c is execution transfer parameter [-], k_t is regression parameter with average value of 1.25 [-], R^{-1}_{ACC} is inverse effective carbonation resistance of concrete [(mm^2/year)/(kg/m^3)], ε_t is error term with average value of 315.5 [(mm^2/year)/(kg/m^3)], C_s is CO_2 concentration [kg/m^3] and $W(t)$ is weather function [-].

The *fib*-Bulletin 34 [6] was chosen because it allows the carbonation depth to be obtained while taking into account both the environment and curing conditions and concrete properties. A previously formed database [4] was used. *Fib*-Bulletin 34 [6] proposed an accelerated test with a CO_2 concentration of 2% for 28 days. If a different CO_2 concentration is used, for example, the new European standard for accelerated carbonation resistance EN 12390-12 [14] specifies a CO_2 concentration of 3% for 70 days, R^{-1}_{ACC} values can be calculated using the expression defined in the LIFECON D 3.2 Service Life Models project [13]:

$$R_{ACC}^{-1}=\left(\frac{x_c}{\sqrt{2\cdot C_s\cdot t}}\right)^2 \quad (2)$$

where, x_c is the average carbonation depth (m), C_s is CO_2 concentration (kg/m^3) and t is the duration (s) of the accelerated carbonation test.The use of Eq. (2) enables the use of the results of any accelerated carbonation test for calculation of R^{-1}_{ACC} [8].

3 Definition of parameters for the probabilistic approach of service life design

The important aspect in selecting the prediction model (*fib* model) is the nature of the input data. If parameters are treated as continuous stochastic variables, defined by mean values, standard deviations, and probabilistic density functions, the model is probabilistic. A fully probabilistic approach makes it possible to determine the service life that is characterized by a defined probability of failure. Therefore, it was decided to apply the fully probabilistic approach in this study. Based on this, it is possible to define the limit state function of reinforcement depassivation caused by carbonation as follows:

$$\begin{aligned} g\left(c,x_c\left(t\right)\right)&=c-x_c\left(t\right)=\\ &=c-\sqrt{2\cdot k_e\cdot k_c\cdot\left(k_t\cdot R_{ACC}^{-1}+\varepsilon_t\right)\cdot C_s\cdot t}\cdot W\left(t\right)\end{aligned} \quad (3)$$

where c is concrete cover (mm).

The value of the nominal concrete cover is usually chosen in terms of the environment in which the concrete will be used. The corresponding design value for different exposure classes is defined in EN 1992-1-1 [9]. Although strictly determined, its actual value in practice varies due to the inevitable irregularities that occur during the construction phase. Therefore, this parameter should be considered as a stochastic variable instead of a constant value. However, for the calculation of service life from a durability point of view, instead of nominal concrete cover, which is a stochastic variable, the minimum concrete cover from durability conditions ($c_{min,dur}$) should be used. This depth is a deterministic value and represents the minimum concrete cover depth necessary in order to achieve the desired service life. In EN 1992-1-1 [9] a minimum concrete cover in the range of 15 to 30 mm is prescribes for exposure classes from XC1 to XC4, for a standard S4 structural class corresponding to a service life of 50 years. The final (nominal) value of the concrete cover (c_{nom}) will be increased by a typical standard deviation for concrete covers (Δc_{dev}), which depends on the type and quality of execution works:

$$c_{nom}=c_{min,dur}+\Delta c_{dev} \quad (4)$$

To solve the limit state function, it is necessary to define certain parameters, first of all the exposure conditions. The mean atmospheric CO_2 concentration (C_s) was estimated by the *fib*-Bulletin 34 [6] as 0.00082 kg/m³ or 0.05% by volume, taking into account that the current value will increase even more (due to the greenhouse gas effect). According to some data [13], the standard deviation is fairly constant at 0.0001 kg/m^3.

The execution transfer parameter (k_c) takes into account the influence of concrete curing conditions on the carbonation resistance. All measures taken to prevent premature concrete drying (water treatment, air conditioning while the surface of the concrete is covered, etc.) are considered to guarantee proper curing. The execution transfer parameter is defined as:

$$k_{cur}=\left(\frac{t_c}{7}\right)^{b_c} \quad (5)$$

where, t_c is period of curing (days), and b_c is regression exponent (-).

It should be emphasized that the value of the exponent b_c in Eq. (5) can vary depending on the type of concrete. For instance, a slow pozzolanic reaction of fly ash may require longer curing time in order to achieve the highest possible carbonation resistance. Van Den Heede [16] noted that, for concrete with fly ash, the recommended values proposed in *fib*-Bulletin 34 [6] can still be used. The mean value (–0.567), standard deviation (0.024) and normal distribution have been adopted for the b_c exponent. The curing period (t_c) of 7 days was adopted because it is assumed that this is the standard time of curing on site, as well as the curing time prescribed in *fib*-Bulletin 34 [6] for the accelerated carbonation test.

The environmental function (k_e) takes into account the influence of natural relative humidity (RH_{real}) on carbonation depth:

$$k_e = \left(\frac{1 - \left(RH_{real} / 100 \right)^{f_c}}{1 - \left(RH_{ref} / 100 \right)^{f_c}} \right)^{g_c} \tag{6}$$

where, RH_{real} is environment relative humidity (%), RH_{ref} is referent relative humidity (%), f_c is exponent (–) and g_c is exponent (–).

As proposed in the *fib*-Bulletin 34 [6], parameter k_e represent the relative humidity of the carbonated concrete, instead of the environmental humidity. Due to the fact that these data are not easily available and that the carbonation process takes place only in the concrete surface layer, it is reasonable to use the values of environmental relative humidity. Such data for RH_{real} is usually collected from the meteorological stations near the site location. Since the lower relative humidity limit is significantly different from zero and the upper limit is 100%, it is appropriate to assume that these parameters are beta-distributed with the upper and lower limits. In this study, a lower limit of 40% and an upper limit of 100% were adopted. An assessment of relative humidity and distribution parameters for particular exposure classes, has been carried out in accordance with the descriptions that can be found in EN 1992-1-1 [9] and relevant studies [13]. Adopted values are presented in Table 1.

Certain specificities existed only within the classes XC1 and XC4. For the XC4 class, wetting and drying cycles were presented through a large standard deviation (16%), where as the mean value was taken based on recommendations from the literature [6,13,17]. The XC1 class represents two opposite exposure conditions: completely wet or completely dry. The relationship between the carbonation depth and relative humidity is a parabolic curve, with a maximum of 50% to 60% *RH* [18–20]. In other words, the carbonation depth under dry or extremely high humidity conditions should be similar. This is based on a physical model of the carbonation process. Under dry conditions, the CO_2 available in the air cannot be dissolved in pores (due to a lack of humidity), which slows down the carbonation process. On the other hand, under extremely high humidity, CO_2 cannot diffuse through the saturated pore solution, which also slows down the carbonation process. The environmental function should reflect the nature of the process. However, parameter k_e, as already emphasized, represents the relative humidity of the carbonated concrete layer rather than the relative humidity of the environment. According to Eq. (6), the value of the parameter k_e under dry conditions is up to 36% higher compared with conditions of moderate humidity (RH = 65%). This causes a problem in determining the service life under dry conditions. Since the XC1 class defines structures under dry or extremely high humidity conditions, a high relative humidity of 92% [13] was used to determine the concrete service life for this class. This will lead to more reliable results for the XC1 exposure class. The adopted beta distribution functions for all exposure classes are presented in Figure 1.

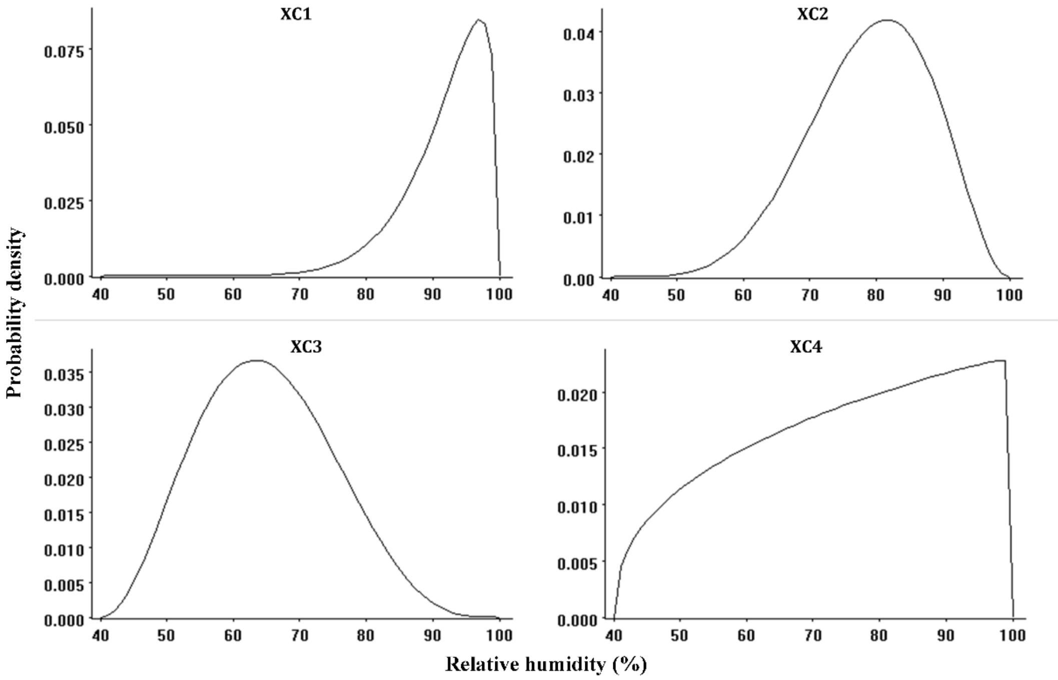

Figure 1. The beta distributions with adopted parameters for all exposure classes [21]

Table 1. Input parameters of the limit state function for service life prediction

Parameter		Distribution	μ	σ	Unit
$c_{\mathrm{min,dur}}$	XC1	Constant	15	–	mm
	XC2	Constant	25	–	mm
	XC3	Constant	25	–	mm
	XC4	Constant	30	–	mm
RH_{real}	XC1	Beta	92 (40*)	6 (100*)	%
	XC2	Beta	79 (40*)	9 (100*)	%
	XC3	Beta	65 (40*)	10 (100*)	%
	XC4	Beta	75 (40*)	16 (100*)	%
RH_{ref}		Constant	65	–	%
f_c		Constant	5.0	–	–
g_c		Constant	2.5	–	–
t_c		Constant	7	–	days
b_c		Normal	–0.567	0.024	–
C_s		Normal	0.0008	0.0001	kg/m³
t		Constant	50	–	year
k_t		Normal	1.25	0.35	–
ε_t		Normal	315.5	48	(mm²/year)/(kg/m³)
R^{-1}_{ACC}		Normal	variable	CoV 10%	(mm²/year)/(kg/m³)

* Lower and upper limit of the beta distribution

The mean values for k_t and ε_t and their distribution functions are proposed in the *fib*-Bulletin 34 [6]. For the weather function, it was adopted that the concrete was sheltered from rain in order to obtain the maximum carbonation depth (the most unfavourable case). The only unknown parameter in this limit state function is the inverse effective carbonation resistance (R^{-1}_{ACC}). Since the determination of the limit value was the subject of this study, the value of R^{-1}_{ACC} was varied. A normal distribution with a coefficient of variation (CoV) of 10% was used.

Overviews of the applied distributions (mean value, standard deviation, lower and upper bound) for each of the input parameters of the limit state function are shown in Table 1.

The reliability index (β) and the probability of failure (P_f) associated with the limit state function (Eq. (3)) was calculated using the *First Order Reliability Method* (FORM). According to the *fib*-Bulletin 34[6], in order to qualify concrete for use, the reliability index must meet the requirements for the depassivation limit state ($\beta \geq 1.3$), which corresponds to $P_f \leq 0.10$.

4 Results and discussions

The relationship between the reliability index and R^{-1}_{ACC} is shown in Figure 2 for all carbonation exposure classes.

Using a defined reliability index ($\beta \geq 1.3$), the maximum values of the inverse effective carbonation resistance for all exposure classes were determined, assuming the minimum concrete cover for each exposure class given in [9]. Since R^{-1}_{ACC} represents the inverse carbonation resistance, an increase in the coefficient represents a decrease in the resistance and vice versa. Therefore, the upper limit of the R^{-1}_{ACC} value was determined.The relationship between exposure classes and the inverse effective carbonation resistance for the service life of 50 years is shown in Table 2. The values in Table 2 represent the average value of the upper limit that needs to be achieved, as well as the maximum deviation of the individual sample. The maximum deviation of an individual sample was determined based on CoV of 10%.

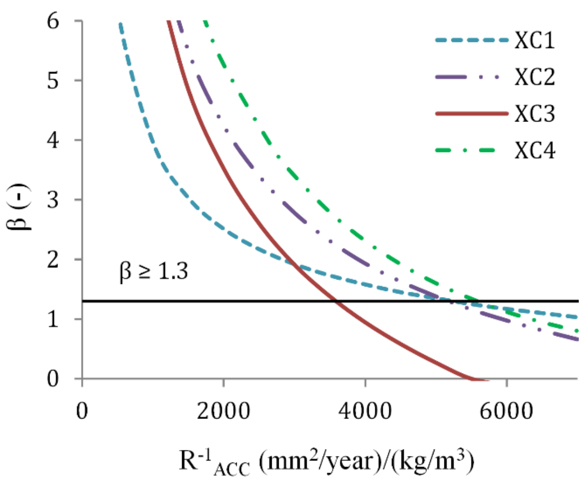

Figure 2. The relationship between reliability index and R^{-1}_{ACC}

As previously mentioned, extreme environments (very high or low humidity) slow down the carbonation reaction considerably. For the exposure class XC1, which represents a very dry or humid environment, the allowed average value is 5200 (mm²/year)/(kg/m³). Although the exposure class XC2 represents a more aggressive carbonation environment, a similar value (5150 (mm²/year)/(kg/m³)) was determined. The reason was the higher concrete cover depth prescribed in EN 1992-1-1 [9] for exposure class XC2 compared to XC1 (see Table 1). Exposure class XC3 represents a moderate humidity environment, and as such, is most suitable for carbonation development. It is therefore not surprising that the lowest value of the inverse effective carbonation resistance is obtained for the XC3 exposure class. Also, the prescribed concrete cover depth (25 mm) is the same as for exposure class XC2, which represents a less harsh environment.

Table 2. Average and maximum values of R^{-1}_{ACC} for different carbonation exposure classes

Exposure class	R^{-1}_{ACC}(mm²/year)/(kg/m³)	
	Average	Maximum
XC1	< 5200	5700
XC2	< 5150	5650
XC3	< 3600	3950
XC4	< 5600	6150

Although wet and dry cycles prolong the depassivation time, the constant change in relative humidity leads to an increase in the corrosion rate during the propagation phase [21] and therefore the highest inverse effective carbonation resistance for XC4 exposure class. However, EN 1992-1-1 [9] as well as the *fib*-Bulletin 34 [6] define service life only through the depassivation phase, not taking into account the propagation period in the service life calculation. The question arises as to whether this concept of prescribing a concrete cover depth for this exposure class (wet and dry cycles) has potentially considered the propagation period. This could open the possibility of considering one part of the propagation period in defining the service life of RC structures.

In addition to the upper limits of R^{-1}_{ACC} for concrete covers defined in EN 1992-1-1 [9], an analysis was also performed for concrete covers in a range of 10-40 mm, Table 3. This allows the determination of the required concrete cover depth for a defined exposure class based on the concrete carbonation resistance tested by accelerated carbonation tests. On the contrary, for the determined carbonation resistance, the table provides the necessary concrete cover. The higher the concrete carbonation resistance, the smaller the concrete cover is required and vice versa. This is in line with the service life design concept.

When comparing values within the same concrete cover depth (c_{min}), the highest values of R^{-1}_{ACC} were obtained for exposure class XC1. These values are several times higher compared to other exposure classes, regardless of the concrete cover depth. This was expected, given that this exposure class represents the least aggressive environment. R^{-1}_{ACC} values for exposure class XC2 were approximately three times lower than those for exposure class XC1. For exposure classes XC3 and XC4, the values were similar regardless of the concrete cover depth. The values of R^{-1}_{ACC} for exposure class XC3 were up to 8% lower compared to XC4. Having this in mind, the concrete cover depth for these two exposure classes should be the same.

As already mentioned, the R^{-1}_{ACC} values presented in Table 3 are calculated based on the measured carbonation depth under accelerated conditions. For practical application, the expected average values of accelerated carbonation depth (x_c) after 28 days under 2% CO_2 were calculated and shown in Table 4. These values are indicative because they are the result of probabilistic analysis, which implies certain assumptions, especially in terms of relative humidity and their distribution functions. However, this approach enables us to have an indication of the concrete quality in terms of carbonation resistance as well as suitability for the designed exposure class and concrete cover immediately after the measurement of carbonation depth after the accelerated test.

Expected values of carbonation depth after 28 days of exposure to 2% CO_2 range between 1.5 mm and 15 mm, depending on the exposure class and the concrete cover depth. The use of other accelerated tests, such as EN 12390-12 [14], is also possible, but values in Table 4 must be recalculated using Eq. (2) according to the exposure conditions defined in that test (CO_2 concentration and test duration).

Table 3. Average values of R^{-1}_{ACC} ((mm²/year)/(kg/m³)) for different exposure classes and concrete covers (c_{min})

Exposure class	c_{min} (mm)						
	10	15	20	25	30	35	40
XC1	< 2100	< 5200	< 9500	< 15000	< 21500	< 29500	< 38500
XC2	< 650	< 1700	< 3200	< 5150	< 7500	< 10200	< 13500
XC3	< 400	< 1150	< 2200	< 3600	< 5200	< 7200	< 9500
XC4	< 430	< 1250	< 2350	< 3800	< 5600	< 7600	< 10000

Table 4. Expected average values of accelerated carbonation depth x_c (mm) after 28 days under 2% of CO_2 for different carbonation exposure classes and concrete covers

Exposure class	c_{min} (mm)						
	10	15	20	25	30	35	40
XC1	< 3.4	< 5.4	< 7.3	< 9.2	< 11.0	< 12.8	< 14.7
XC2	< 1.9	< 3.1	< 4.2	< 5.4	< 6.5	< 7.6	< 8.7
XC3	< 1.5	< 2.5	< 3.5	< 4.5	< 5.4	< 6.3	< 7.3
XC4	< 1.6	< 2.6	< 3.6	< 4.6	< 5.6	< 6.5	< 7.5

5 Conclusions

Since carbonation has become an important issue in the durability analysis of RC structures, it was necessary to find a simple way in which the results of the accelerated carbonation test could be used in service life design. Therefore, the objective of this study was to determine the limit values of accelerated carbonation resistance to satisfy the required service life of RC structures with concrete covers as prescribed in EN 1992-1-1. The service life of 50 years was considered, as well as all carbonation exposure classes (from XC1 to XC4). A full probabilistic analysis was conducted using the *fib*-Bulletin 34 carbonation prediction model and FORM analysis. For the defined reliability index and minimum concrete cover depth defined by EN 1992-1-1, the upper limits of the inverse effective carbonation resistance for all exposure classes were determined (Table 2).

Also, values of R^{-1}_{ACC} for different exposure classes and for concrete covers in a range of 10-40 mm are calculated in Table 3. In this way, it is possible to adopt the required concrete cover depth for a defined exposure class, based on the concrete carbonation resistance, which is in line with the service life design concept. In addition to this, and taking the values of R^{-1}_{ACC} from Table 3, the carbonation depths after conducting accelerated tests were determined, which gives an early indication of concrete quality in terms of carbonation resistance (Table 4).

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