

Prediction of the reinforced concrete structure durability under the risk of carbonation and chloride aggression

L. CZARNECKI^{1*} and P. WOYCIECHOWSKI²

¹ Building Research Institute, 1 Filtrowa St., 00-611 Warsaw, Poland

² Department of Building Materials Engineering, Warsaw University of Technology, 16 Armii Ludowej Ave., 00-637 Warsaw, Poland

Abstract. The paper presents an idea of predicting durability of concrete structures with steel reinforcement under conditions of chloride and carbonation corrosion risk. Mechanisms of destruction due to steel corrosion in such conditions are shown. The recently elaborated model of carbonation and general model of chloride diffusion have been discussed. An algorithm of the rest service life time prognosis has been shown and options of its main stages realization have been done. An example of durability prognosis for pre-stressed hollow-core floor slab with upper layer of concrete and epoxy-resin coating has been given. This example confirms the usefulness of the described prognosis method and demonstrates its helpfulness in a structure management according to the standards of EN 1504 series.

Key words: concrete durability, chloride aggression, carbonation, durability prognosis.

1. Introduction

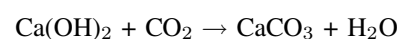
Expected durability of the structure results from the assumed service life, in which structure should fulfill its functions in the usability, capacity and stability. The established service life is the basis for design of structures but the design should also take into account the environmental conditions (classes of exposition), in which the individual elements will function. The expected durability of the structure should be ensured by a proper structure design, an appropriate selection of materials and the required quality of execution. An actual state of the object as a rule, however, differs from the assumed state among others, due to various defects. Some defects are detected at the stage of erection and acceptance of the object and, where possible and appropriate, removed. Some defects, however, could not be removed completely, others appear only after a long time of exploitation. Moreover, in the course of exploitation, impacts inconsistent with established conditions of use may occur (failures, inappropriate use, etc.). Such circumstances cause more intensive processes of “aging” than it would appear from the requirements adopted for the assumed service life. In this case, it is necessary to predict residual service life, basing on research and analysis of the structure and to estimate the expected shortening of durability. Prognosis of durability, although, burdened with uncertainty, may constitute an important prerequisite for determining how to proceed with the structure – the decision to repair, repair design, the investor claims in respect of guarantees and warranties, etc. In the case of reinforced concrete structures, reduction of durability may be caused by the destruction of concrete, reinforcement, or a combination of both processes [1]. In practice, the most common is to reduce the durability components due to corrosion of reinforcement, which is primarily caused by concrete cover carbonation and/or penetration of chloride ions in

concrete [2]. Knowledge of corrosion processes progress over time in real material and environmental conditions is necessary to predict durability of concrete structures. The article presents the author’s model of carbonation and the chloride ion migration model applied to predict the durability of reinforced concrete structures.

2. Carbonation and chloride aggression as the main factors affecting concrete elements durability

2.1. Concrete carbonation – the effect on reinforced concrete, factors regulating the course, models of progress in time, idea of self-terminating nature of carbonation. Concrete carbonation can be defined as the complex physicochemical changes in concrete under long-term influence of carbon dioxide. Carbon dioxide is permanently present in atmospheric air, outside and inside of buildings. A volumetric content of CO₂ in the air is ca. 0.03%, but in industrial zones and along main roads it could be up to 0.3%, or locally more, so that carbonation can progress continuously, especially in concrete with no surface protection [2, 3]. This primarily concerns the elements of engineering structures such as bridges, viaducts, tunnels, road pavements, car parks etc.

A main chemical mechanism of carbonation is reaction of atmospheric CO₂ with calcium hydroxide from cement hydration with release of calcium carbonate and water:



Other concrete compounds, such as lime from hydrated aluminosilicates, can be partially carbonated, but this process is possible only in a high CO₂ concentration and its influence on concrete is limited. The basic carbonation product – calcium carbonate – crystallize in concrete pores. Small quantities

*e-mail: L.Czarnecki@il.pw.edu.pl

of silica, alumina and ferrous oxide are also produced as products of CSH carbonation. A speed of carbonation progress in time depends on external conditions as well as on concrete properties and processes of structure execution. The main negative effect of carbonation is decreasing of concrete pH, which is one of most frequent cause of reinforcement corrosion and ferrocement destruction. Carbonation can be considered as one of most important factors causing concrete structures destructions [3, 4].

The speed of carbonation is determined by different internal and external factors. Among external factors very important are: CO₂ concentration, humidity and air temperature. Internal factors are related to concrete composition, type and content of binder and water-cement ratio, which determine tightness of concrete microstructure. Also an early curing of concrete plays an important role. Generally, the speed of carbonation:

- increases, proportionally to square root, CO₂ concentration in the air,
- increases with increase of humidity up to 70-80%, where more important is humidity of concrete than air, but if pores are fully water saturated, a speed of carbonation decreases,
- increases with cyclic changes of temperature and pressure,
- increases with increase of water-cement ratio,
- decreases with tightening of concrete structure,
- decreases with increase of cement content in concrete.

The prognosis of changes of depth of carbonation in time is possible with the use of mathematical models of carbonation process in time. Such models were presented by many authors – Wieczorek [5], Slopkova [6], Papadakis [7], Ishida/Maekawa [8] and others. Foundation of their models was Fick's law, which describes a speed of diffusion. The final result of carbonation modeling is a power function of time with exponent 1/2.

$$h = A(t)^{1/2} + B, \quad (1)$$

where h – depth of carbonation, t – time of exposition, A, B – coefficients which depends on internal and external factors.

Different researchers show in their works different forms of such a model, with the use of supplementary variables, such as w/c , CO₂ concentration, time of early curing and others [4, 7, 8]. The presumption that carbonation process is a power function of time of exposition, is equivalent to find a process as unlimited in time, and its range unlimited in the depth of concrete. Fick's law refers to a gas diffusion through substance immutable in time and for such a case formula (1) would be justified. But concrete is a material in which deep physicochemical changes occur in time, due to the carbonation process. Changes of pores structure, overgrowth of pores by carbonation products, lead to changes of CO₂ diffusive ability in time, which can cause decreasing of the carbonation process, down to stabilizing its range on the constant depth. This nature of phenomenon was mentioned by Fagerlund [9], Fiertak [4], Slopkova [6].

The research aim was to prove self-terminating nature of carbonation process. Scientific research was conducted within

many years in the Department of Building Materials Engineering at Warsaw University of Technology. Results were a foundation of many publications and PhD Thesis of Więclawski [10–13].

Those works conclude that concrete carbonation in urban-industrial conditions can be described with hyperbolic function of time (reciprocal square root of time), which have asymptotic value parallel to time axis. This asymptote is a limit of carbonation depth. Traditional and hyperbolic models of carbonation are showed in Fig. 1. Hyperbolic carbonation model has a following form:

$$h = a(w/c) + b(cp) + c(t^{-0.5}), \quad (2)$$

where h – depth of carbonation, mm, w/c – water-cement ratio, cp – early curing time, days, t – time of exposition, years, a, b, c – coefficients which describes relevance of influence of w/c , 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 CO₂ concentration. Similar models were elaborated for different types of concrete, particularly with the use of Portland cement and cement incorporating slag and fly ash. SEM analysis shows different density of concrete structure in the carbonated and non-carbonated zone. It was stated that all results are in accordance with hyperbolic model $h = f(1/t^{0.5})$, regardless of binder composition, but various function characteristic coefficients were obtained for various cements. The 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.

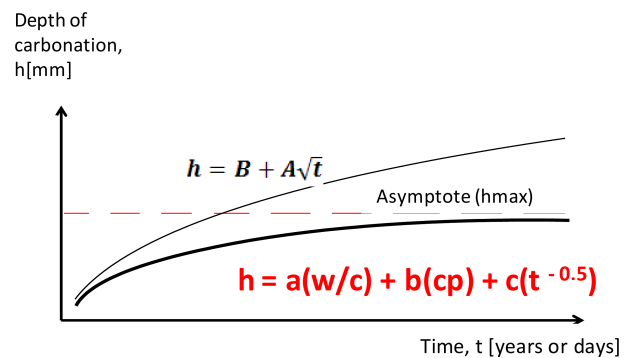


Fig. 1. Power and hyperbolic models of carbonation

2.2. Chloride aggression – effect on reinforced concrete, source of chloride, factors regulating migration, model of chloride diffusion in concrete. Chloride ions Cl⁻ are highly aggressive to steel reinforcement. The chloride concentration growth on a steel surface up to critical value leads to corrosion cell formation and rapid change of steel potential. This is associated with passive layer damage by Cl⁻ ions. The chloride critical concentration level depends on hydroxyl ions content in concrete, which is related to cement type, additives and course of carbonation, resulting in the OH⁻ ions

content decreasing. Usually, it is assumed that steel depassivation in concrete takes place when Cl^- ions content to OH^- ions content ratio exceeds 0.6 [2, 5].

Chloride corrosion of reinforcement is pitting type and leads to cross section reduction with simultaneous deposition of corrosion products in anodic zone. The corrosion products have a larger volume than initial bar volume, so the mechanical destruction of concrete cover takes place. This type of corrosion is associated with both impact of the chloride from environment, as well as with the presence of chlorides in concrete components. This last factor is limited by the requirements of the standards for the aggregates, cement type, admixtures and additives.

To predict the course of chloride corrosion, the model of Cl^- ions migration in concrete is needed. Diffusion of chlorides in concrete is the complex process and changes over time. Partially ions can be bound by concrete components (e.g. Friedel salt formation) but release of ions bounded in concrete components is also possible [14]. The necessary condition for chloride diffusion is moisture in capillary pores, wherein the higher is the degree of pores saturation with water – the faster is the diffusion. In air-dry pores chloride migration ceases. In the literature [2, 3, 14–16] a model of chloride diffusion is given. It results from solution of Second Fick's Law equation with use of error function *erf* for transient flow conditions:

$$C_x/C_0 = 1 - \text{erf}[x/2(D \cdot t)^{0.5}], \quad (3)$$

where C_0 – chloride concentration on concrete surface, %; $C_{x,t}$ – chloride concentration AT a distance x from surface after migration time t , %; D – diffusion coefficient, cm^2/s ; t – migration time, s.

This model allows to determine the apparent diffusion coefficient for the concrete in construction on the basis of chloride penetration test and determines the time when the critical concentration would reach the depth of reinforcement [17].

2.3. Critical conditions for initiation of corrosion in reinforced concrete elements. It is assumed [1, 2, 18] that the moment of initiation of reinforcement corrosion indicates the failure of durability, although, it is not the failure of load limit state. Under this condition, it can be assumed that the residual service life is equal to the time of initiation of corrosion (T_{cor}). It is certainly true for pre-stressed structures, where both the reinforcement construction (tangle of thin tendons), as well as corrosion effects (catastrophic failure), argue for such a sharp durability criteria. In the case of reinforced concrete structures, it is possible to consider the further course of corrosion of reinforcement after initiation, until a reduction in cross-section of the reinforcement threatens the load capacity. This involves the structural analysis of element and estimation of reinforcement cross-section loss which cause equalization

of stress and load capacity. Estimation of corrosion rate under given conditions (steel type, environment) is also necessary. This allows not only to predict residual service life (T_{cor}) but also residual lifetime (time to load capacity failure).

Carbonation depth – decreased pH front vs concrete cover thickness. A real risk of reinforcement corrosion, due to carbonation, is associated with decreasing pH of the concrete cover to a critical level, at which the depassivation of steel occurs. Even a slight reduction of the natural pH of the concrete decreases protective properties of the concrete cover. A pH level of about 11.5 already is considered to be threatening to the reinforcement. Standard measuring methods concerns phenolphthalein indicator, which allows to determine a depth of pH = 8.3 front in carbonated concrete [19]. At such a low pH level corrosion is highly probable. It is also possible to use other chemical indicators, such as thymolphthalein (pH front – 10.5) thymol-phenolphthalein (pH front – 9.6) or even universal indicator (rainbow test) [12]. Whatever the low pH value is considered to initiate corrosion, the subject of evaluation is always a progress of carbonation front (the selected pH) to the reinforcement. After the time when the selected pH value reaches its level a reinforcement can be considered as the time of corrosion initiation. Significantly, the rate of carbonation changes over time. The constant value of this rate should not be used to estimate the time, when carbonation front reaches the level of reinforcement, although this procedure is also indicated in the literature [1–3]. An appropriate procedure requires testing a carbonation progress in time and develop a model of this process for a certain concrete. The model can be determined by an accelerated method at elevated CO_2 concentration. The rate of carbonation in these conditions is greater than in natural conditions, but its maximum value – the asymptote by the model (2) – is similar in both cases. This self-terminating nature of carbonation process was shown in previous authors publications [10–12].

When predicting durability in the conditions of corrosion caused by carbonation, is necessary to adopt two significant assumptions, that determine both the prediction methodology and its result (Table 1):

- a critical pH level for the initiation of reinforcement corrosion,
- a method to determine maximal depth of carbonation.

Each of the conceptions presented in Table 1 can be used in the durability prognosis and identified limitations resulting from an assumption can be considered as elements of the prognosis uncertainty.

The authors of the paper often used in their research phenol-thymolphthalein indicator and determined the time of reaching the reinforcement by the carbonation front according to method 1 or 4 from Table 1.

Table 1
Basic assumptions for predicting element durability under risk of corrosion due to carbonation

Assumption 1: Critical pH value for corrosion initiation		
	pH values	Brief SWOT analysis
1	8,3 (phenolphthalein)	<ul style="list-style-type: none"> – value much lower than actual limit of corrosion initiation – testing procedure is standardized (PN EN 14630) – low variability of testing results
2	9,6 (thymol-phenolphthalein)	<ul style="list-style-type: none"> – value slightly lower than real limit of corrosion initiation – lower variability of tests results than for thymolphthalein indicator
3	10,5 (tyhmolphthalein)	<ul style="list-style-type: none"> – a value close to the actual limit of corrosion initiation – high variability of testing results
4	Rainbow test (wide range of pH values)	<ul style="list-style-type: none"> – opportunity to measure few pH limits on one concrete break – blurred limits between colors corresponding to neighboring pH values, which makes measurement less accurate
Assumption 2: The method of determining the time at which the carbonation front reaches the reinforcement		
	Method	Brief SWOT analysis
1	Developing a model based on results of accelerated laboratory carbonation tests performed on samples made of specified concrete	<ul style="list-style-type: none"> – precise prediction of carbonation depth after at any time of exposition – the need of making laboratory samples from the same concrete as in the construction – testing time min. 3 months
2	Developing a model based on results of accelerated laboratory carbonation tests performed on samples taken from construction	<ul style="list-style-type: none"> – precise prediction of carbonation depth after at any time of exposition – unknown influence of “shock” change of carbonation rate on results – testing time min. 2 months
3	Adopting an average rate of carbonation on the basis of knowledge about the composition and characteristics of concrete, and data from the literature	<ul style="list-style-type: none"> – no need to carry out tests, which significantly reduces time of prognosis developing – average rate of carbonation from literature is burdened with high error
4	Measurement of the depth of carbonation in element and calculation the rate of carbonation on the basis of current exploitation time	<ul style="list-style-type: none"> – “in situ” test allows to refer estimation to the actual state of concrete in construction – calculation assuming linear progress of carbonation in time, which is burdened with significant error, which is the greater if the shorter would be time of carbonation

Table 2
Classes of chloride content in concrete according to selected reference documents

No.	Reference document	The criterion for selection of chloride content class	Chloride content class	Property adopted as a criterion	Maximum limit value, %	
1	European standard: EN 206-1	With no reinforcement steel or other metal except corrosion-resistant handles	Cl 1.0	The maximum permissible content of Cl ⁻ relative to the mass of the cement, defined as the sum of the chloride content in concrete components (without specifying the test method)	1.0	
		With steel reinforcement or other metal	Cl 0.20		0.20	
			Cl 0.40		0.40	
		With pre-stressed steel reinforcement	Cl 0.10		0.10	
2	German national complementary standard to DIN- EN 206-1: DIN 1045-2	With no reinforcement steel or other metal except corrosion-resistant handles	Cl 1.0		1.0	
		With steel reinforcement or other metal	Cl 0.40		0.40	
		With pre-stressed steel reinforcement	Cl 0.20		0.20	
		Pre-stressed concrete or reinforced heat curing concrete	Cl 0.10		0.10	
3	British national complementary standard to BS-EN 206-1: BS 8500-1	Post-tensioned concrete	no data		Determine individually	
		Reinforced concrete with sulfate resistant Portland cement	Cl 0.20		0.20	
			Cl 0.30		0.30	
		Concrete reinforced with ordinary steel	Cl 0.40		0.40	
4	ACI 318-05 Building code requirements for structural concrete	Pre-stressed concrete	–	The maximum permissible content of Cl ⁻ soluble in water, relative to the mass of the cement	0.06	
		Reinforced concrete expose to chloride in service	–		0.15	
		Reinforced concrete used in dry conditions and protected from moisture	–		1.00	
		Other reinforced concrete constructions	–		0.30	
5	ACI 222R-01 Protection of metals in concrete against corrosion	Pre-stressed concrete	-	The maximum permissible content of Cl ⁻ soluble in water or acid, relative to the mass of the cement	water	acid
		Reinforced concrete used in wet conditions	–		0.06	0.08
		Reinforced concrete used in dry conditions	–		0.08	0.10
					0.15	0.20

Chloride ions – critical concentration for different conditions. The chloride corrosion threat is associated with the chloride migration through the pores of the concrete until a critical concentration of Cl⁻ ions reaches the surface of the steel reinforcement. The critical value of a chloride content which initiates corrosion is expressed in reference documents as a percent of cement mass in concrete. Critical values are understood as total content of chlorides from concrete components (aggregate, cement, water, admixtures and additives) and from external sources. These values differ in reference documents [20-25] both due to different testing methods and due to the characteristics of the element and its conditions of use (Table 2). An applicable test method (dissolving in water or in acid) leads to significantly different results. The higher critical concentration is adhered to the method of dissolution in acid. Differentiation of requirements depending on the characteristics of the element comprises a method of reinforcement (reinforced, pre-stressed, post-tensioned concrete) and the conditions of production and exploitation (wet condition of use, external access of chlorides, heat treatment in production). Initiation of corrosion, however, is associated primarily with the damage of the passive layer on steel, occurring after exceeding the critical values of Cl⁻ and OH⁻ ions molar concentration ratio. Most of the standard criteria result from the estimation of the intensity of corrosion of steel in the described conditions (for example: high stresses in the pre-stressing steel, moisture intensifying the transport of corrosion factor). Assuming a critical value of the chloride ions concentration, on the basis of guidance given in Table 2, is a necessary step in predicting the durability of an element.

3. The algorithm of the concrete structure durability prognosis in terms of corrosion risk

Durability of a construction or an element is usually needed to predict when the deterioration process, which could shorten a service life of an element, is observed. The main aim of the prognosis is to adopt the appropriate structure management options, according to EN 1504-9 [26]. This standard (in Sec. 5) provides different options of structure management, ranking from “do nothing for a certain time but monitor”, through “re-analyze the structural capacity, possibly leading to downgrading in function”, “prevent or reduce further deterioration”, “strengthen or repair and protect all or part of the concrete structure” to “reconstruct or replace all or part of the concrete structure” or “demolish all or part of the concrete structure”. The prognosis of durability is thus an important tool for decisions on the repair principle and the repair design according to the requirements of standards EN 1504 series.

The recommended approach to the durability prognosis could help not only to manage the construction during its service life but also to create construction robustness at the stage of designing. This would involve different scenarios of construction life.

The algorithm of prognosis (Fig. 2) includes “in situ” diagnostic tests and laboratory tests on the samples taken from the structure and computational analysis, conducted on the basis of the obtained results. The prognosis, as a rule, is carried out, assuming that no repair will be done. At the first stage it is necessary to identify the main structural parts of the object and determine its technical condition, including, in particular, defects and damage affecting durability. Then the environment conditions for the elements should be identified, including classes of exposition according to EN 206-1 [20] and EN1992-1-1 [27]. Based on the analysis of the findings above and the analysis of the design documentation, it shall be determined which components of the structure are most at risk of corrosion. For the selected elements the subsequent analysis of durability is carried out, independently for carbonation and chloride aggression risk.

With regard to the risk of carbonation, predicting the durability involves estimation of time T_{carb} , when the carbonation front reaches a depth of the steel reinforcement, using methods and indicators given in Table 1. Obtained time T_{carb} is the residual service life of the element until the initiation of corrosion caused by carbonation. In case of significant cracks in element, it is recommended to check the depth of carbonation in cracks, in which the rate of carbonation is usually greater than in non-cracked place.

With regard to the risk of chloride aggression, predicting the durability involves:

- determination of the critical concentration of Cl⁻ for a given element (the element type, conditions of element production and exploitation, methods of determination of Cl⁻ content),
- determination of diffusion coefficient of Cl⁻ ions in the concrete, based on measurements of chloride concentrations at the surface and in the depth of concrete, with use of methods specified in Chapter 2.2,
- identification of possible routes of chlorides penetration to the reinforcement. External sources of Cl⁻ should be established, places where they are in contact with an element, routes of their transport, including the flow of polluted water, which is in many cases the main source of chlorides.

Knowing the critical concentration, diffusion coefficient and migration routes, the times to reach the critical concentration for reinforcement (t_{Cl1} , t_{Cl2} , ... t_{Cln}) can be determined for different routes of migration. The shortest of these times T_{Cl} , calculated as follows:

$$T_{Cl} = \min (t_{Cl1}, t_{Cl2}, \dots t_{Cln}) \quad (4)$$

is considered a residual service life of the element, remaining to initiate chloride-induced corrosion.

Minimum of T_{carb} , t_{Cl1} , t_{Cl2} , ... t_{Cln} , allows to estimate the expected residual service life of the element (T_{cor}) under conditions of corrosion caused by chlorides and carbonation:

$$T_{cor} = \min (T_{Cl}, T_{carb}). \quad (5)$$

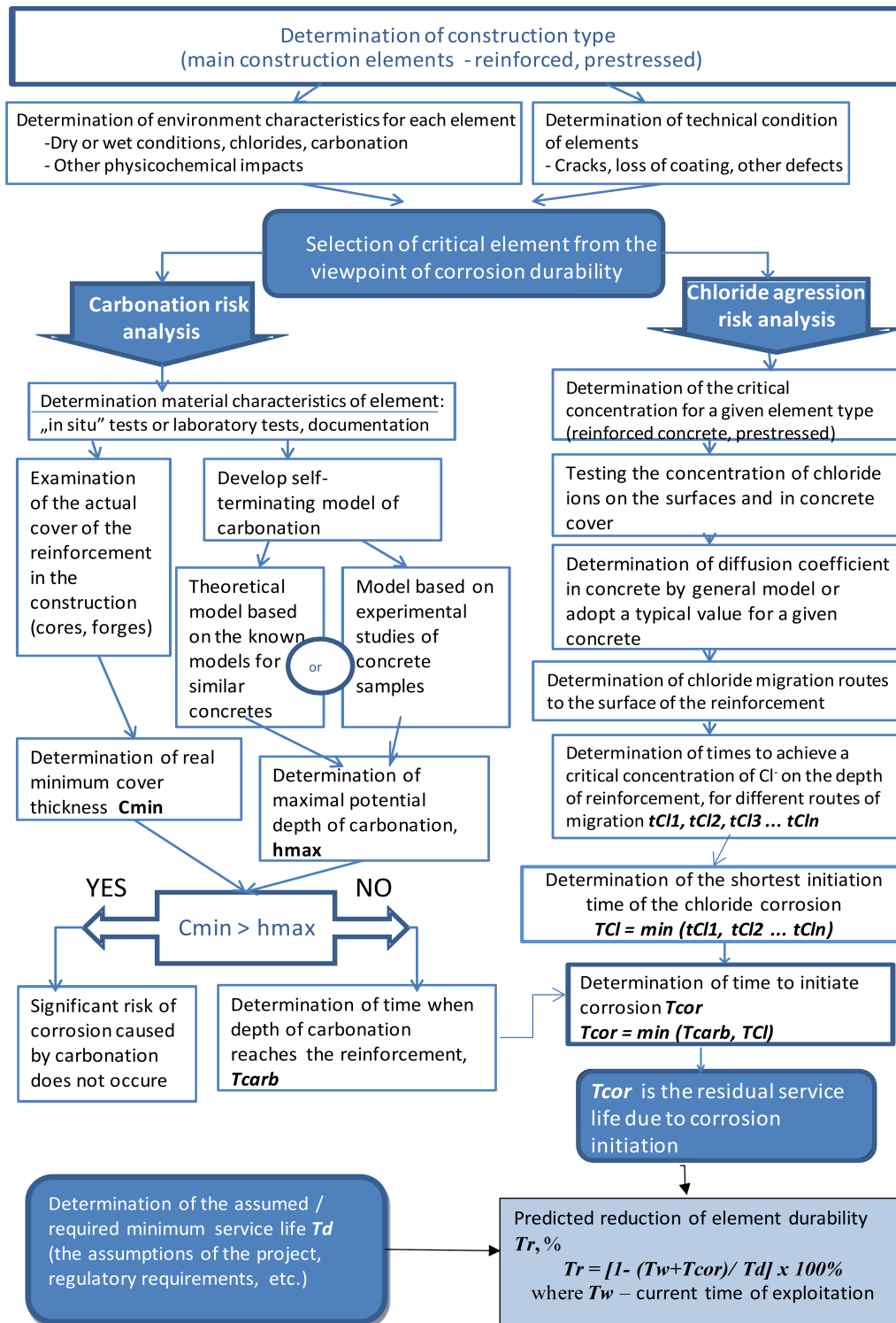


Fig. 2. The algorithm of durability prognosis for element under risk of chloride aggression and carbonation

Following the above analysis based on measurements in the construction and on samples taken from the construction, ensures that the synergistic effect of chloride migration processes and carbonation will be taken into account. Synergism of carbonation processes and migration of chloride, affects the characteristics of concrete examined in the construction (carbonation depth, diffusion coefficient). Therefore,

it is included in the prognosis through the adoption of actual concrete properties to the modeling and prediction. In the case of predictions based solely on the basis of laboratory tests or indicators drawn from the literature, the prognosis is subject to greater error, resulting not only from the approximate values of adopted characteristics, but also from difficulties in taking into account the synergic effect.

Knowledge of T_{cor} and T_w (current time of exploitation) values allows to calculate a reduction of element durability $T_r, %$ as follows:

$$T_r = [1 - (T_w + T_{cor}) / T_d] \times 100, \quad (6)$$

where T_d is designed service life durability of element.

4. Example of durability prognosis – pre-stressed floor slab with upper concrete layer under risk of corrosion

The investigated floor slab was constructed of pre-stressed hollow-core elements, which were supported on precast joists and columns. On the surface of hollow-core slabs an upper concrete layer with anti-shrinkage mesh was made. As a surface protection an epoxy-resin thin-film coating has been used (Fig. 3).

After 5 years of exploitations cracks and other defects were observed on the surface of the floor. Some cracks went through the entire thickness of the floor. Incorrect shaping of the surface, causing the accumulation of polluted water on the surface of the floor, was also determined. Cracks were the migration route for water through the floor and into the holes in pre-stressed elements. Water was polluted with chlorides from the winter road maintenance chemicals.

Analysis of the construction elements showed that the most exposed to corrosion are hollow-core slabs. Upper con-

crete layer was not considered as composite element for increasing load capacity of the floor but only an industrial floor element. Studies of chlorides content and carbonation progress in parts of the floor were made on the samples taken from the construction.

It was found out that the carbonation of concrete upper layer (tested with thymol-phenolphthalein indicator) in cracks reached or exceeded the level of anti-shrinkage mesh and corrosion was visible. It was stated, however, that this process concerns non-structural element, which can be treated as replaceable, so its destruction doesn't affect a service life of construction. Carbonation of hollow-core slabs was also tested and there was no measurable depth of carbonation, with accuracy to 1 mm. It was concluded, that risk of service life reduction of the construction due to carbonation is insignificant.

The concentration of chloride ions was studied on the surface of floor slabs and inside concrete, at a depth of 10 mm from the top surface (Fig. 4). The presence of chloride ions with a similar concentration as on the upper surface of the slabs, was stated also on their lateral surfaces (in the joints of adjacent slabs), as well as inside the hole. Using equation (3), the diffusion coefficient was determined for different cross-sections of floor slab. The coefficient ranged from $D1 = 1 \times 10^{-8}$ to $D2 = 2.0 \times 10^{-7} \text{cm}^2/\text{s}$. Higher value $D2$ corresponds with cracked cross-section of slab and lower – with non-cracked.

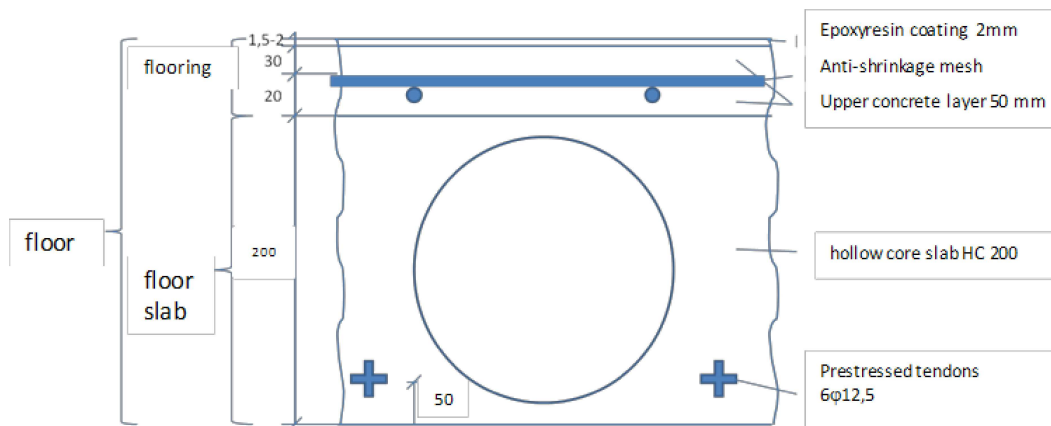


Fig. 3. Floor construction

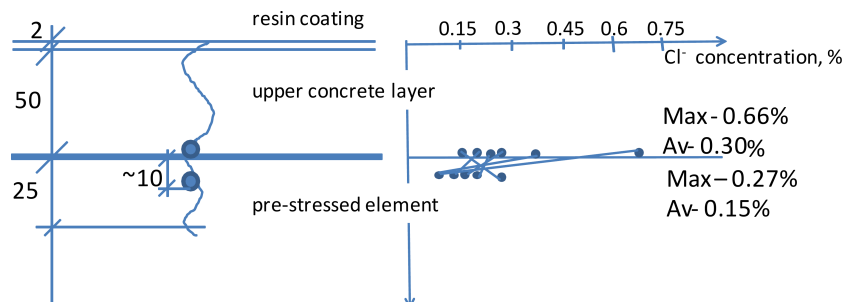


Fig. 4. The distribution of chloride concentrations on the surface and the upper zone of precast slab

Chloride migration possible routes to pre-stressing tendons have been determined, analyzing floor construction (Fig. 5). A discussion on the critical concentration of Cl^- ions, resulting in the initiation of corrosion in tendons, led to the conclusion that permissible chloride content class for pre-stressed heat-cured element is C10,10 (Table 2, pos. 3).

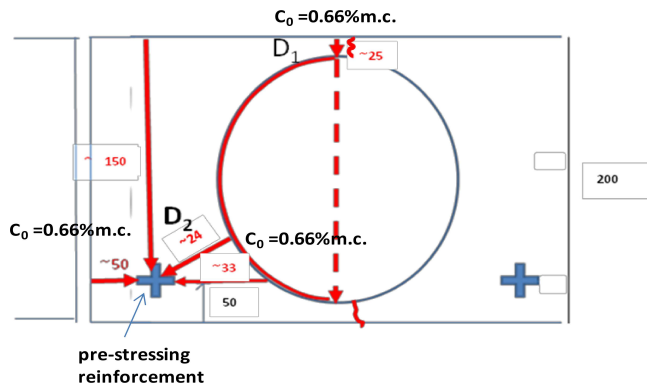


Fig. 5. Routes of migration of chloride ions to pre-stressing tendons in the floor slab, dimensions in [mm]

Finally, to predict the durability, the following assumptions have been adopted:

- critical concentration of Cl^- ions in concrete **$C_{x,t} = 0.1\% \text{ c.m.}$**
- diffusion coefficient through crack to the hole in slab **$D_1 = 2.0 \times 10^{-7} \text{ cm}^2/\text{s}$**
- diffusion coefficient in concrete (from hole to tendon or from lateral surface to tendon) **$D_2 = 1.0 \times 10^{-8} \text{ cm}^2/\text{s}$**
- maximum chloride concentration on the slab surface **$C_0 = 0.66\% \text{ mass of cement.}$**

On the basis of the determined values, time t_{Cln} to achieve Cl^- ion concentration of 0.1% on the surface of pre-stressing tendons (Table 3), has been determined with the use of formula (4).

Table 3
 Estimation of time of corrosion initiation in pre-stressing tendons

$C(x,t) = 0.1\% \text{ m.c.}, D_1 = 2.0 \times 10^{-7} \text{ cm}^2/\text{s}$
 $D_2 = 1.0 \times 10^{-8} \text{ cm}^2/\text{s} C_0 = 0.66\% \text{ m.c.}$

Migration route, mm	25+33	50	33	24
Time to reach concentration $\text{Cl}^- = 0.1\% \text{ c.m.}$ on the level of tendons, t_{Cln} , years	13	11	9	5

The analysis, taking into account the risk of chloride aggression and carbonation, allows to conclude, that the residual service life (T_{cor}) for the floor in the pessimistic scenario was equal to $T_{Cl} = 5$ years (Table 3). It is probable if chloride ions would penetrate from the hole to tendons through the shortest way. In case of longer migration way this period will extend to maximum 13 years.

For load-bearing elements such as floor slab, an expected service life according to the regulations of Eurocodes [27, 28] should not be less than 50 years, ($T_d = 50$ years). Taking

into account 5-year period of exploitation ($T_w = 5$ years) and calculated residual service life values ($T_{cor} = 5 \div 13$ years) it could be estimated, that there was 65–80% reduction of floor slab durability T_r .

5. Conclusions

Predicting durability of reinforced concrete elements under conditions of the corrosion threat is an important part of building diagnostics. This is important both technically (safety in use, the decision to repair, repairing method), as well as formally and economically (the actual value of the structure, guarantee, warranty).

The presented method allows, on the basis of scientific research and mathematical models of processes, to achieve engineering purposes, i.e., determine the approximate residual service life and reduction of durability in relation to the designed value. The prognosis is usually done under the assumption, that no protective and repairing actions will be taken. Concluding is carried out in relation to the pessimistic scenarios. The interpretation of results should take into account the uncertainty, with which a prognosis is charged. This uncertainty results from the inaccuracy of estimation of the materials characteristics and from the variability of environmental impacts. Prognosis durability by the proposed algorithm can be useful in determining the structure management options according to the standards series EN 1504. The recommended approach to the durability prognosis could help not only to manage the construction during its service life but also to create construction robustness at the stage of designing.

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