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Research paper

Carbonation of concrete cover of reinforcement as a cause of loss of durability of structures

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Abstract: The article discusses the physical and chemical mechanisms of the carbonation phenomenon itself, as well as points out the synergistic effect of frost destruction and concrete carbonation on reinforced concrete elements. Examples of structural damage from engineering practice in the diagnosis of reinforced concrete structures are presented. Two cases of frost and carbonation damage of precast reinforced concrete elements are analyzed. It was noted that the most common cause of damage to concrete structures is the lack of frost resistance. Carbonation of concrete leads to deprivation of the protective properties of the concrete lagging against the reinforcing steel. The examples cited include precast elements that, for technical reasons, had a relatively small lagging thickness. The first one relates to the thin walled elevation elements, which are exploited during 60 years and the second relates to the energetic poles with very advanced concrete corrosion damage. The examples given of corrosion of concrete and reinforcement of elements indicate that synergistic environmental interactions can intensify the destruction of elements.

Keywords: carbonation of concrete, corrosion of concrete, cover of reinforcement, durability of structures, frost resistance of concrete, synergy of frost and carbonation resistance

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1. Durability of concrete

According to EN 1990: "structures shall be so designed that changes occurring during their design life, taking into account environmental effects and the anticipated level of maintenance do not reduce the performance of the structure below the intended level". [1]. Durability should therefore be understood as the period of time during which the level of performance of a structure is maintained above a critical value for a given period of its use. Furthermore, the durability of concrete has always been attracted wide attention in the construction field because it is connected with safety, economy and sustainability [2].

According to EN 1990:2004 "a structure shall be designed and constructed in such a way that during its intended life, with adequate reliability and without excessive costs:

– it shall take up all influences and impacts which may be expected to arise during its construction and use, it shall remain fit for its intended use, the structure shall be designed so that its load-bearing capacity, serviceability and durability are adequate" [1]. Reliability is defined as the ability of a structure or element to meet specific requirements of load-bearing capacity, serviceability and durability in a projected period of use, which is usually expressed in probabilistic measures [3]. Eurocode [1] therefore requires structures to satisfy three fundamental requirements over their intended lifetime: absorption of influences and actions, fitness for use and adequate durability.

The corrosion process is a phenomenon progressing in time and it is not a linear progression. During the initiation period, usually the symptoms are hardly noticeable because they develop locally in the microstructure. During laboratory tests, an initial strengthening of the concrete can often be seen due to the filling of the pores with corrosion products. It is only at a later stage, when the limit stresses resulting from further growth of corrosion products in the pores are exceeded, that cracks, fractures and localized detachments develop. The further corrosion process is usually faster (Fig. 1). In view of the above conditions, the earlier the repair is started, the smaller the scope of repair and the higher its efficiency. Moreover, the basis of effective repair is correct identification of the cause and selection of remedial measures adequate to the identified corrosion mechanism. Doing the repair "blindly" based on identifying only the symptoms and not the causes significantly limits the effectiveness of the repair. In extreme cases, neglect at the diagnostic stage may

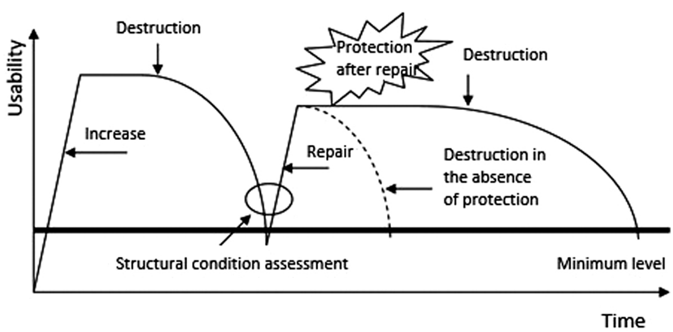

Fig. 1. Utility of an object over time (based on [7])

cause rapid deterioration of the structure, e.g. due to the closure of the corrosive environment under the repair layer. In the repair of concrete structures the same principle applies as in medicine: treat the causes and not the symptoms. The tools for proper handling of concrete protection are contained in the PN-EN 1504 family of standards [4]. A necessary step is to conduct a comprehensive diagnostic study.

The design stage is always key in shaping the durability of concrete. It determines the choice of materials, geometry of elements and surface protection methods. Determination of the construction class according to EC0, EC1 and EC2, taking into account the specific requirements for concrete exposure classes related to carbonation (XC), allows the selection of the minimum concrete cover of a specific strength class ensuring the required durability of the element [1, 5, 6]. The aim of this paper is to highlight the risks associated with synergistic effects of the environment despite the adoption of correct solutions in the light of current technical knowledge.

2. Carbonation phenomenon

Carbonation is a set of physicochemical transformations of concrete under the influence of long-term exposure of carbon dioxide on the concrete surface, which is constantly present in the surrounding atmospheric air and in the atmosphere inside building structures. The concentration of CO_2 varies between 0.03% and 0.3% depending on the location of the concrete structure [8].

Steel reinforcement placed in concrete is protected against corrosion if the concrete is not contaminated with aggressive substances and its pH is high enough to ensure the durability of the passive layer on the surface of the reinforcement. The corrosion of the reinforcement, initiated by the process of cover carbonatation, gradually leads to its destruction. The first stage of carbonatation (Fig. 2a) has no significant negative effects on the structure. When the pH in the reinforcement environment decreases to approx. 11 pH,

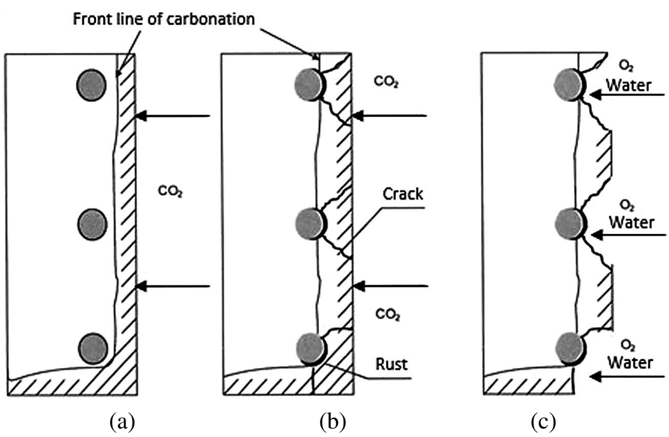

Fig. 2. Stages of destruction of reinforced concrete structure due to carbonation [8]

the passivation state is lost and electrochemical corrosion of reinforcement starts. The appearance of cracks in the cover, through which aggressive substances can easily penetrate, intensifies carbonation (Fig. 2b). In the third stage (Fig. 2c), gradual chipping and spalling of the cover occurs, so that the reinforcement is exposed and this leads to a significant reduction in the durability of the concrete structure [8].

Carbonation significantly decreases the durability of reinforcement in reinforced concrete structures, mainly due to a decrease in the pH of the concrete, however, positive effects are observed with respect to concrete. The number and size of pores in the carbonated zone are reduced, which results in a tightening of the concrete microstructure. Additionally, increased surface hardness and strength of the near-surface layer of carbonated concrete is observed [8–10].

Many external and internal factors influence the intensity and rate of carbonation. Decisive factors include the type of concrete, the amount of cement, the w/c ratio, the method of concrete compaction, the care of the concrete, the climatic and environmental conditions under which the concrete structure is subsequently placed. As far as external factors are concerned, the most important are CO_2 concentration, humidity and air temperature. Among the most important internal factors, the tightness of the concrete, indirectly dependent on the w/c ratio, as well as the type and quantity of the bond, are the main determinants [11].

Concrete cover protects steel reinforcement against corrosion, provides fire resistance and ensures cooperation of reinforcement with concrete, of course provided that the structure is properly designed and constructed. The nomogram presented below (Fig. 3) suggests the possible depth of carbonatation in view of the type of cement used, strength class and selection of minimum lagging thickness for exposure class XC structures. When selecting the lagging, it is worthwhile to refer to the guidelines contained in Eurocode 2 – PN-EN 1992-1-1 [5], where the most commonly selected construction class S4 refers to the design life of the structure of 50 years (Table 1). The construction class can also be determined on the basis of the designed strength class, the designed service life of 100 years, the shape of the structure and with special control of the concrete quality.

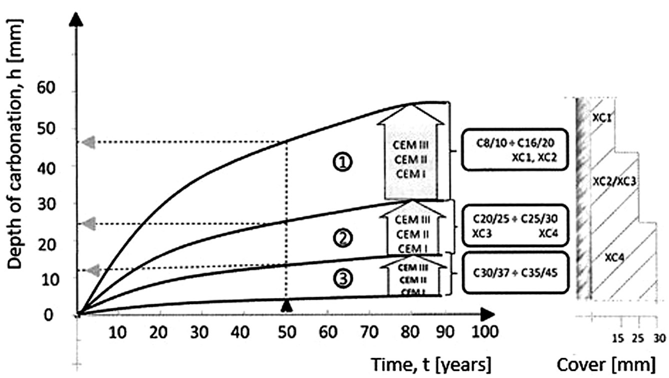

Fig. 3. Required thickness of lagging due to approximate extent of carbonation resulting from concrete strength class and cement type [8, 9]

Table 1. Minimum cover required for durability of reinforcing steel [5]

Environmental requirements							
Construction class	Exposure class						
	X0	XC1	XC2/XC3	XC4	XD1/XS1	XD2/XS2	XD3/XS3
S1	10	10	10	15	20	25	30
S2	10	10	15	20	25	30	35
S3	10	10	20	25	30	35	40
S4	10	15	25	30	35	40	45
S5	15	20	30	35	40	45	50
S6	20	25	35	40	45	55	55

3. Synergistic effect of corrosion interactions

Environmental and climatic conditions have a significant impact on the condition and durability of unprotected reinforced concrete elements. The most common cause of damage to concrete structures is the lack of frost resistance. Carbonation of concrete leads to deprivation of protective properties of concrete cover in relation to reinforcing steel (CO_2 penetrates concrete and reacts with water-soluble components of hardened cement grout). The combination of these two phenomena (a synergistic effect that is not considered in traditional design methods) can lead to a significant reduction in the durability of concrete structures.

Frost corrosion in temperate climates, where concrete is subjected to cyclic freezing and thawing, much of it additionally in the presence of de-icing salts, is a very common phenomenon. Frost corrosion occurs by increasing the volume of water as it freezes and with interacting high stresses – cracks and fissures are noticed in the concrete. When the freezing temperature and concrete temperature curves intersect in the interior of the concrete slab, freezing of water will occur near the top surface of the concrete and deep into the structure (Fig. 4). As the outside temperature decreases, the rest of the water will freeze and the result is damage (bursting) to the top surface of the concrete [7].

It is worth mentioning the synergy of influences that contribute to the deterioration of the durability of the structure. The environment in which concrete "lives" is the atmosphere, water and soil. In cold regions, the action of freeze–thaw (FT) cycles is regarded as the main cause of concrete deterioration. The coupling actions between FT cycles and chemical actions, such as chloride penetration, sulfate attack, carbonation and alkali–silica reaction cannot be ignored because the combination of different degradation processes may be more severe than that of processes acting separately. The synergetic effects between different physical degradation processes must also be considered [12]. Prevailing climate in Poland is characterized by a large variability of weather. Winters can be cold as well as mild, and summers hot or rainy. In Poland, for more than 9 months of the year, the relative air humidity is higher than 75%, quite high but constant pollution in the form of CO_2 emissions is observed.

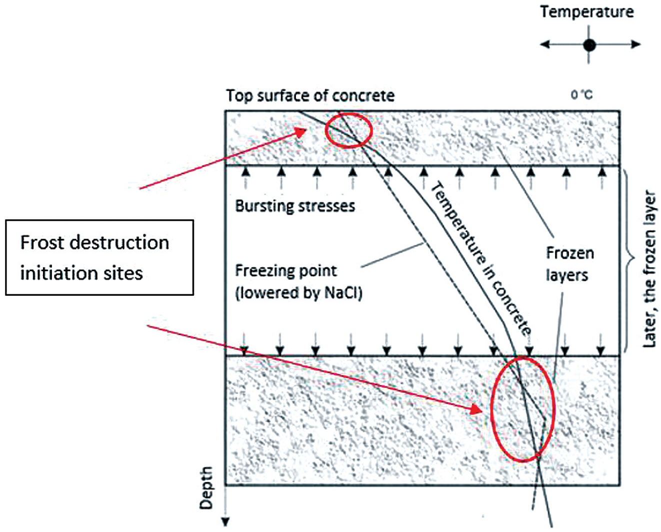

Fig. 4. Frost corrosion mechanism of concrete slab in the presence of de-icing salts (based on [7])

There are many damaged structures in which the synergic effect of corrosion interactions is visible. In general, for the cause of deterioration of concrete structures, a deterioration phenomenon called synergistic deterioration is often observed, in which the characteristics of deterioration generated by the interaction of various phenomena [13]. This paper presents examples from engineering practice examples from engineering practice in which destruction of reinforcement cover is shown.

4. Prefabricated facade elements of a religious building

The presented example is a front elevation of the over 60-year-old St. Michael Archangel Church in Warsaw. The analysis of this case was an interesting study of the durability of filigree concrete profiles exposed on a representative facade, in difficult environmental conditions of the center of Warsaw. Advanced damage to the precast concrete occurred mainly on the front elevation elements of the church [14].

The tests, measurements, and observations showed extensive damage to the facade elements (Fig. 5a). The damage included separation of external vertical edges of the elements and horizontal cracks on the internal side of the elements. The cracks on the inside ran horizontally approximately in the middle of the element height. The external detachments affected practically all elements along the entire height of the facade. The damage to the elements from the outside ran along the reinforcement bars and affected the entire thickness of the reinforcement cover. The reinforcement of bars with a diameter of 6 mm and a reinforcement cover thickness of less than 2 cm in combination with low concrete quality (sandcrete with up to 2 mm aggregate) were factors that promoted corrosion of the reinforcement and resulted in fragments of the reinforcement cover falling off. The corrosion mechanism is primarily related to the phenomenon of carbonation – during the diagnostic work, complete carbonation of the cover and a far-reaching corrosion of the bars were found (Fig. 5b). As a result of the depletion of the facade durability, the safety of users was endangered, due to the falling of detached fragments and, in the long run, the risk of losing the stability of the self-supporting facade wall [14].

(a) (b) (c)

Fig. 5. View of extensive damage to façade elements (a); Example of element chipping (b); Measurement of carbonation depth and lagging (c)

The causes of facade damage may include errors resulting already at the stage of designing elements according to standards from over half a century ago, as well as those related to the quality of materials used at that time and low production standards compared to contemporary prefabricated factories. The concrete used in the elements was characterized by a very fine grain size and probably (after macroscopic evaluation) quite low cement content. The thickness of the lagging in case of side surfaces of the elements was even only several millimeters, which resulted from the geometry of thin-walled facade elements (Fig. 5c).

The reinforcement of the elements was made of Ø 6 mm plain bars, potentially very susceptible to corrosion. These material characteristics would be unacceptable under current precast design standards. The low-quality materials adopted and the low degree of reinforcement of the elements also affected their overall stiffness during operation in the self-supporting wall of the facade – this was reflected in the regular pattern of cracks running horizontally usually at the mid-height of the individual elements. When analyzing the durability of the facade, one should also take into account the environmental changes in the area of the church, originally located outside the very center of Warsaw, which, as the capital developed, found itself in a more aggressive zone of influence of urban pollution.

5. Prefabricated infrastructure elements

Prefabricated elements presented here in the form of columns belong to the group of medium-dimensional bar elements of power infrastructure. Elements of this type are characterized by a small cross-section, which means that the possibility of shaping their durability by choosing the reinforcement cover of increased thickness is limited. In view of the above, the quality of the materials used, including the type of aggregate, concrete composition (w/c ratio) and the type of admixtures and additives used.

The operating conditions of the elements in certain circumstances may be quite specific due to the previously mentioned synergistic effect of external influences. In the case of the energy infrastructure elements under consideration, particular attention should be paid to the ground zone of the elements. The impact of the carbon dioxide-containing atmosphere and cyclic temperature changes obviously covers the element at full height. When it comes to the ground zone, conditions are slightly different due to additional cycles of varying humidity. These are related to the occurrence of a splash zone during precipitation, the occurrence of moisture in the vegetation zone, or the prolonged evaporation of soil moisture over time.

The above cumulation of environmental impacts creates “optimal” corrosion conditions (maximum rate of carbonation, highest intensity of frost damage, variable atmospheric

a) b) c)

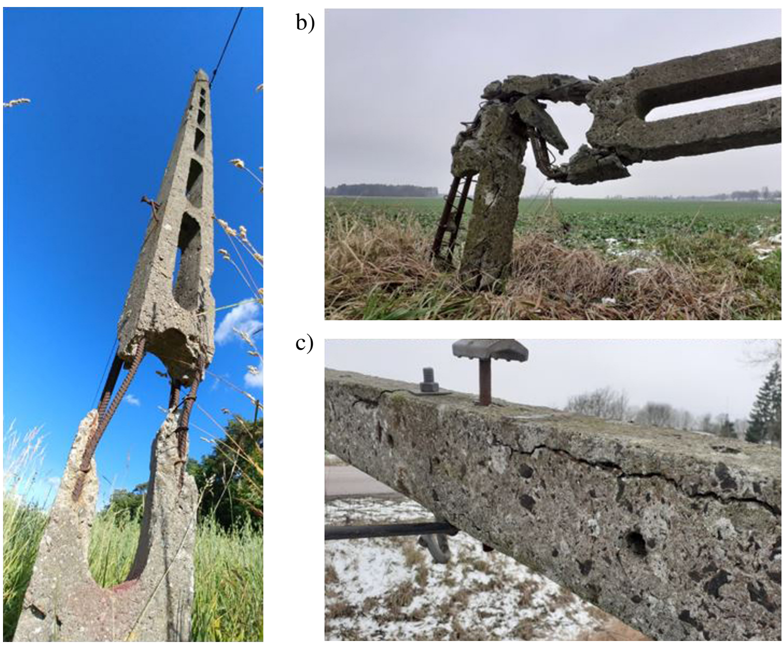

Fig. 6. View of the damaged pole (a); Extensive detachment reinforcement cover in the element (b); Destruction of the element (c)

humidity) of the concrete cover. Cracks appearing on the structure reduce the aesthetics of the element and signal the formation of significant deterioration processes, as well as condition the serviceability limit state, an extreme example of which at the end of the element's service life is shown in Fig. 6c. Corrosion of the cover progresses quite slowly in the initial period, however after exceeding a certain stage it becomes completely detached (Fig. 6a,b), which in case of thin elements means absolute necessity of immediate reaction – usually element replacement.

6. Conclusions

The issue of durability of reinforced concrete structures and simultaneous maintenance of safety during the service life of a given object requires appropriate consideration and analysis of the combination of physical, physicochemical, chemical and electrochemical phenomena in the expected operating conditions of concrete. The examples given of corrosion of concrete and reinforcement of elements indicate that synergistic environmental interactions can intensify the destruction of elements. The presented considerations prove that the way of selecting the reinforcement cover due to the threat of carbonation, as imposed by EC2 [5], does not take into account the synergistic effect, which may determine the real resistance of the system to environmental interactions. Durability design based on the concepts of carbonation resistance [15], frost resistance and mutual synergy [16] are the basis of the projected new edition of Eurocodes, in which not only exposure classes but also classes of resistance of structures to these hazards will appear.

The mentioned examples include prefabricated elements, which for technical reasons had a relatively small cover thickness. Despite the aggressive environment, however, it should be noted that these elements showed surprisingly high durability, especially considering the period when they were made. This can be attributed to the repeatedly claimed [17–20] characteristics of prefabrication technology related to controlled industrial production conditions, repeatable production technology, accuracy and repeatability of assembly.

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Karbonatyzacja betonu otuliny zbrojenia jako przyczyna utraty trwałości konstrukcji

Słowa kluczowe: karbonatyzacja betonu, korozja betonu, otulina zbrojenia, trwałość konstrukcji, mrozoodporność betonu, synergia mrozoodporności i karbonatyzacji

Streszczenie:

W artykule omówiono mechanizmy fizyczne i chemiczne samego zjawiska karbonatyzacji, jak również zwrócono uwagę na synergiczne działanie destrukcji mrozowej i karbonatyzacji betonu na elementy żelbetowe. Przedstawiono przykłady uszkodzeń strukturalnych z praktyki inżynierskiej w zakresie diagnostyki konstrukcji żelbetowych. Przeanalizowano dwa przypadki uszkodzeń mrozowych i karbonatyzacyjnych prefabrykatów żelbetowych. Zauważono, że najczęstszą przyczyną uszkodzeń konstrukcji betonowych jest brak mrozoodporności. Karbonatyzacja betonu prowadzi do pozbawienia właściwości ochronnych otuliny betonowej względem stali zbrojeniowej. Przytoczone przykłady dotyczą elementów prefabrykowanych, które ze względów technicznych miały stosunkowo niewielką grubość otuliny. Pierwszy z nich dotyczy cienkościennych elementów elewacji, eksploatowanych w okresie 60 lat, a drugi dotyczy słupów energetycznych z bardzo zaawansowanymi uszkodzeniami korozyjnymi betonu. Podane przykłady korozji betonu i zbrojenia elementów wskazują, że synergiczne oddziaływania środowiskowe mogą intensyfikować destrukcję elementów.

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