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SERVICE LIFE PREDICTION'S ALGORITHM: LOADING, CARBONIZATION, CHLORIDE AGRESSION

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Abstract

Corrosion reinforcement marine hydraulic structures due to chloride aggression and carbonization of concrete leads to a sharp decrease in the safety of the structure. The steel reinforcement will be subjected to a so-called depassivation process, once the chloride concentration on surface exceeds a certain threshold concentration, or the pH value in the protective layer of concrete decreases to a threshold value due to carbonation. Electrochemical reactions begin to occur with the formation of corrosion products with the penetration of oxygen on the steel reinforcement surface. This leads to cracking of the protective layer of concrete. It should also be taken into account that, due to corrosion mechanisms, the cross-sectional area of the reinforcement also decreases. The article suggests a method for predicting the complex degradation of reinforced concrete structures, taking into account various mechanisms of corrosion wear, which will allow developing effective ways to improve the durability and maintainability of structures operated in the marine environment.

Keywords: structure, concrete, corrosion, carbonation, chloride aggression.

АЛГОРИТМ ПРОГНОЗИРОВАНИЯ СРОКА СЛУЖБЫ: НАГРУЗКА, КАРБОНИЗАЦИЯ, ХЛОРИДНАЯ АГРЕССИЯ

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Реферат

Коррозионное армирование морских гидротехнических сооружений из-за хлоридной агрессии и карбонизации бетона приводит к резкому снижению сохранности конструкции. Стальная арматура подвергнется так называемому процессу депассивации, когда концентрация хлоридов на поверхности превысит определенную пороговую концентрацию или значение pH в защитном слое бетона снизится до порогового значения из-за карбонизации. Электрохимические реакции начинают протекать с образованием продуктов коррозии с проникновением кислорода на поверхность стальной арматуры. Это приводит к растрескиванию защитного слоя бетона. Также следует учитывать, что из-за механизмов коррозии площадь поперечного сечения арматуры также уменьшается. В статье предложен метод прогнозирования комплексной деградации железобетонных конструкций с учетом различных механизмов коррозионного износа, который позволит разработать эффективные способы повышения долговечности и ремонтопригодности конструкций, эксплуатируемых в морской среде.

Ключевые слова: структура, бетон, коррозия, карбонизация, хлоридная агрессия.

1. Research overview

The influence of the marine environment on the intensity of corrosion requires additional research, because chloride aggression and concrete carbonization significantly accelerate the degradation process [21]. Reinforcement corrosion due to chloride alone is well understood and a number of models are available to simulate this process. Some models study the transport mechanism of chloride ions from the surface of reinforced concrete elements, others [4, 5-9] study the effect of initial cracks in concrete [10-12] and the effect of loading on the transport mechanism of chlorides [18, 19].

In [16], a numerical simulation of the process of corrosion damage to concrete was proposed, in which the physical and electrochemical models are associated with a mechanical model of crack formation. There are known works on the study of joint environmental factors: chloride aggression and carbonization [13-15]. It is noted that the effect of carbonization on the diffusion coefficient of chloride ions depends on the types and proportions of the concrete mixture. In [14-15], a variable test with chloride exposure and carbonation is described, where the concentration of chloride ions was maximum near the carbonization front.

Despite the fact that carbonization and chloride aggression occur simultaneously in the marine environment, it should be noted that the diffusion of chloride ions is much faster than the carbonization process. Before carbonation, concrete usually contains Friedel's salt due to the chloride ion bound within the concrete. When Friedel's salt reacts with carbon dioxide, chloride ions are released into pore water [23]:

$$3CaO \cdot Al_2O_3 \cdot CaCl_2 \cdot 10H_2O + 3CO_2 \rightarrow 3CaCO_3 + 2Al(OH)_3 + CaCl_2 + 7H_2O \qquad (1)$$

The released ions increase the concentration of free chloride, significantly exceeding the concentration of chloride ions, which are transported from the surface to the internal environment. Therefore, to analyze and predict the combined effect of carbonation and chloride penetration, it is necessary to model how carbonation interacts with chloride transport without carbonation. The authors proposed a complex model of the combined action of carbonation and chloride aggression, which is compared with chloride transfer without carbonization and is verified experimentally.

2. Carbonization model

The effect of carbonization is to reduce the alkalinity of the porous medium in concrete, which allows the passive film on the reinforcement to be destroyed and thereby initiate corrosion, leading to chipping of the concrete protective layer and a decrease in strength. Thus, concrete carbonization is a complex physicochemical process. The description of this process is based on the differential equation of the first law of A. Fick [4]:

$$J = -D\frac{dc}{dx} \qquad (1)$$

If we consider carbonization as a stable constant process described by this law, then the deterministic model of the depth of passage of the carbonization front for a structure is written as follows [4]:

$$x_c(t) = \sqrt{\frac{2D(t)}{a}\int_1^t f_T(t)\cdot f_W(t)\cdot k\cdot C_{CO2}(t)\,dt}\cdot\left(\frac{t_0}{t}\right)^n \qquad (2)$$

where t is the operating time in years; t_0 – 1 year; n is the age factor; k is a coefficient that takes into account the increased content of carbon dioxide in large cities; $f_T(t)$ and $f_W(t)$ are functions of temperature and humidity changes in time, respectively; $C_{CO2}(t)$ – function of changing the concentration CO_2 in time; $D(t)$ – diffusion coefficient of carbon

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dioxide in concrete, as a function of time; a – the amount of CO_2 required for the conversion of all hydration products capable of carbonization, is determined by the formula [1]:

$$a = 0.75 \cdot CaO \cdot b \cdot a_H \cdot \frac{M_{CO2}}{M_{CaO}} \qquad (3)$$

where CaO is the content of calcium oxide in the cement; b is the amount of cement; M_{CO2} – molar mass of carbon dioxide; M_{CaO} – molar mass of calcium oxide; a_H – degree of cement hydration.

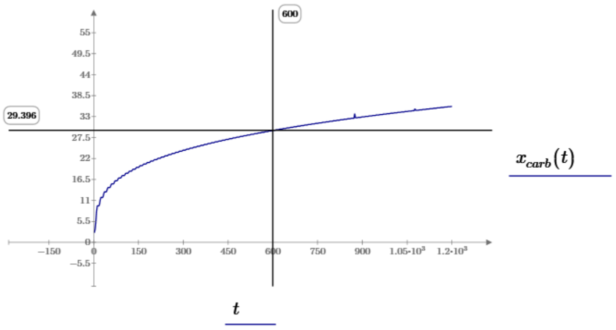
The proposed model was used to calculate the depth of carbonization of the protective layer of concrete of a reinforced concrete shelf structure located at a distance of 10 m from the coastline and flooded only during storms. The structure is operated in the south of Sakhalin Island and is made of reinforced concrete. Concrete class B22.5 with a cement consumption of 350 kg/m³ and a water-binding ratio of 0.4. The design service life of the structure is 50 years.

The initial data of the model are shown in Table 1.

Table 1 – Initial data

Parameter	Value
Average temperature of the warmest month T_max T_{max}	17,7 °C
Average temperature of the coldest month T_{min}	2,4 °C
Average humidity of the wettest month W_{max}	0,85
Average humidity of the driest month W_{min}	0,71
Water-binder ratio *w*/*b*	0,4
Cement consumption *b*	350 kg/m³

Model (2) was calculated using the Mathcad program. The simulation results are shown in Fig. 1.



T – время, мес., $x_{carb}(t)$ – глубина карбонизации

Figure 1 – Graph of changes in the depth of carbonization of concrete of the cover over time

The graph shows that over 50 years (600 months) of operation, the depth of concrete carbonization will be 30 mm or 60 %. The degree of carbonation in this case a_c = 0.6.

3. Chloride diffusion model

The description of the diffusion of chlorides into the protective layer of concrete is based on the equation of Fick's second law [4]:

$$\frac{dc}{dt} = D\frac{d^2c}{dx^2} \qquad (4)$$

Taking into account the binding capacity, the diffusion equation (4) takes the form [4]:

$$\frac{dCf}{dt} = \frac{D_{Cl}}{1+\left(\frac{1}{w_e}\right)\cdot\left(\frac{\partial C_b}{\partial C_f}\right)}\frac{d^2C_f}{dx^2} \qquad (5)$$

where C_f is the concentration of free chlorides in concrete; C_b – concentration of bound chlorides in concrete; D_{Cl} – effective diffusion coefficient of chlorides in concrete; w_e – free pore moisture; $(\partial C_b)/(\partial C_f)$ – binding capacity of concrete.

The bonding capacity of still concrete is often determined by the slope of the bonding isotherm. This study uses the Langmuir isotherm model [4]:

$$\frac{\partial C_b}{\partial C_f} = \frac{\propto_L}{\left(1+\beta_L\cdot\frac{C_f}{b}\right)^2} \qquad (6)$$

The effective diffusion coefficient of chlorides is calculated as [23]:

$$D_{Cl} = D_{cl.0}\cdot f_T(t)\cdot f_W(t)\cdot f_t(t) \qquad (7)$$

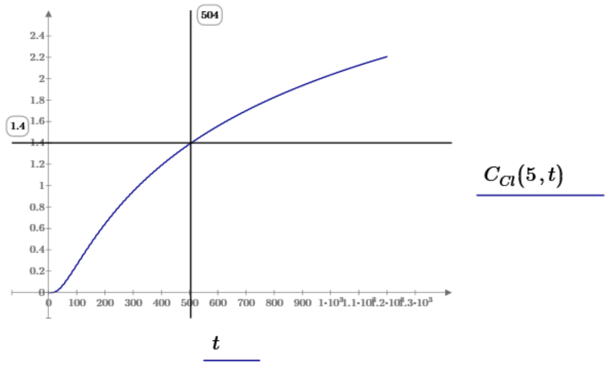
where $f_T(t)$, $f_W(t)$, $f_t(t)$ – respectively, the function of the influence of temperature, humidity and time on the diffusion coefficient; $D_{cl.0}$ – initial diffusion coefficient of chlorides.

Substituting equations (6) and (7) into equation (5), defining the diffusion equation is modified as follows [4]:

$$\frac{d}{dt}C_{Cl} = \frac{D_{cl.0}\cdot f_T(t)\cdot f_W(t)\cdot f_t(t)}{1+\left(\frac{1}{w_e}\right)\cdot\left(\frac{\propto_L}{\left(1+\beta_L\cdot\frac{C_{Cl}}{b}\right)^2}\right)}\frac{d^2}{dx^2}C_{Cl} \qquad (8)$$

The proposed model is used to calculate the concentration of chlorides at the depth of the protective layer of concrete of a reinforced concrete shelf structure, located at a distance of 10 m from the coastline. and flooded only during storms. The structure is operated in the south of Sakhalin Island and is made of reinforced concrete. Concrete class B22.5 with a cement consumption of 350 kg/m³ and a water-binding ratio of 0.4. The design service life of the structure is 50 years. The initial data are presented in table 1.

Model (8) was also calculated in the Mathcad program (Fig. 2)



$C_{Cl}(x;t)$ – концентрация ионов хлорида на глубине защитного слоя X см. в зависимости от времени t, кг/м³. Критическая концентрация хлоридов принята 0,4% или 1.4 кг/м³ по массе вяжщцего

Figure 2 – Graph of the change in chlorides over time (months) without taking into account carbonization at a depth of the protective layer of 5 cm

From the graph in Fig. 2, it can be seen that the level of chloride content in the near-armature zone will reach a critical concentration after 504 months of operation, or approximately 42 years.

4. Model of the combined effects of carbonation and chloride aggression

It is assumed that the transport equation for chloride ions after carbonization still corresponds to Fick's second law of diffusion (5). The total amount of chloride per unit volume of concrete consists of free chloride in the pore solution and bound chloride (Friedel's salt) [23]:

$$C_{Cl,carb} = w_e C_{fc} + C_{bc} \qquad (9)$$

where $C_{Cl,carb}$ is the total chloride concentration, taking into account carbonation; C_{fc} – content of free chlorides in concrete; C_{bc} – content of bound chlorides in concrete, w_e – pore moisture.

Since in a specific case the interaction of concrete with the environment is accompanied not only by the penetration of chloride ions but also by carbonization, the residual binding capacity of concrete after carbonization is reduced.

Based on experimental studies [23], the amount of bound chloride depends not only on the concentration of free chloride in the pore solution, but also on the degree of carbonization, as shown in Fig. 3, therefore it is proposed to replace $\propto_L$ with $\propto_{Lc}$ for concrete after complete carbonization [23]:

$$\propto_{Lc} = \propto_L (1 - d \cdot a_c) \tag{10}$$

where d is the coefficient of the decrease in the binding capacity of chloride ions due to carbonization, taken equal to 0.88 on the basis of research [23].

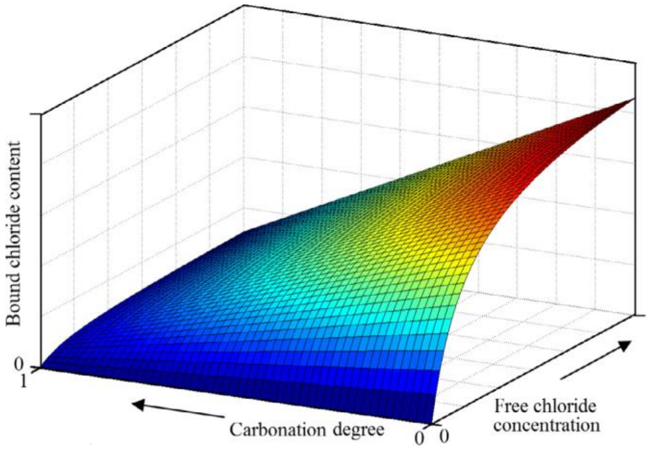


Figure 3 – Changes in the content of bound chloride depending on the concentration of free chloride and the degree of carbonation [23]

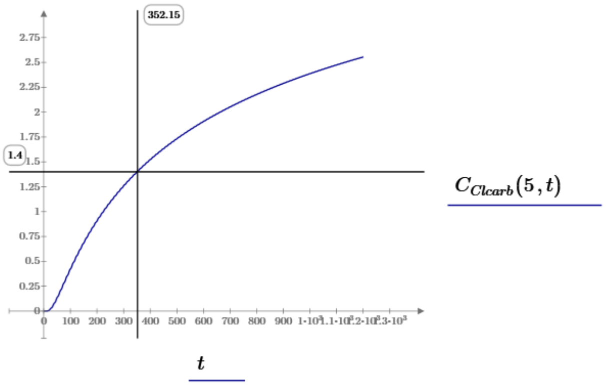
Taking into account equation (10), Langmuir's law (6) taking into account carbonation is as follows:

$$\frac{\partial C_b}{\partial C_f} = \frac{\propto_L (1 - d \cdot a_c)}{(1 + \beta_L \cdot \frac{C_f}{b})^2} \tag{11}$$

Then the governing diffusion equation is modified as follows:

$$\frac{d}{dt} C_{Cl} = \frac{D_{cl.0} \cdot f_T(t) \cdot f_W(t) \cdot f_t(t)}{1 + (\frac{1}{w_e}) \cdot (\frac{\propto_L (1 - d \cdot a_c)}{(1 + \beta_L \cdot \frac{C_{Cl}}{b})^2})} \frac{d^2}{dx^2} C_{Cl} \tag{12}$$

As in the previous case, using the Mathcad program, according to the proposed model, the chloride concentration is calculated at the depth of the protective layer of concrete of a reinforced concrete shelf structure at a distance of 10 m from the coastline. and flooded only during storms. The structure is operated in the south of Sakhalin Island and is made of reinforced concrete. Concrete class B22.5 with a cement consumption of 350 kg/m^3 and a water-binding ratio of 0.4. The design service life of the structure is 50 years. The initial data are presented in Table 1. The simulation results are shown in Figure 4.



t – время (месяцы). C_{Clcarb} $(x; t)$ – концентрация ионов хлорида на глубине защитного слоя X см. в зависимости от времени t, кг/м^3. Критическая концентрация хлоридов принята 0,4% или 1.4 кг/м^3 по массе вяжщщего

Figure 4 – Graph of the change in chlorides over time (months), taking into account carbonization at a depth of the protective layer of 5 cm

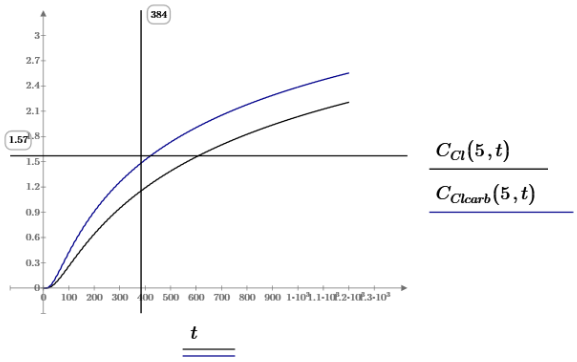
As can be seen from the graph in Fig. 4, the level of chloride content in the near-armature zone will reach a critical concentration after 352 months of operation or after about 29 years, which is strikingly different from the case without taking into account carbonation, where the critical concentration was reached after 42 years.

5. Verification of the model of combined action of carbonization and chloride aggression

To assess the results of the model of the combined action of carbonization and chloride aggression, in 2016 a full-scale survey of port facilities in the south of the island was carried out. Sakhalin. The combined effect of chlorides and carbon dioxide was most clearly traced in the construction of the pedestrian bridge of the Kholmsk sea trade port (Fig. 5). On the basis of the construction passport, the pedestrian bridge was put into operation in 1984. at the time of the survey, its service life was 32 years. The structure is located 10 meters from the coastline, is in the spray zone and is periodically flooded during storms.

Figure 5 – Span of the pedestrian bridge of the Kholmsk sea trade port

The results of measuring the depth of carbonation by phenolphthalein test showed that the depth of carbonation is approximately 25 mm. The level of chloride concentration at the depth of the protective layer of concrete in this case was 1.57 kg/m^3 by weight of the binder.



t – время (месяцы). C_{Cl} $(x; t)$ – концентрация ионов хлорида на глубине защитного слоя X см. в зависимости от времени t без учета карбонизации, кг/м^3. C_{Clcarb} $(x; t)$ – концентрация ионов хлорида на глубине защитного слоя X см. в зависимости от времени t для бетона в следствии комбинированного действия карбонизации и хлоридной агрессии, кг/м^3. Критическая концентрация хлоридов принята 0,4% или 1.4 кг/м^3 по массе вяжщщего

Figure 6 – Comparison of the change in chlorides over time (months) with and without carbonization at a protective layer depth of 5 cm

Figure 6 shows a comparison of the results of modeling the change in chlorides over time with and without taking into account carbonation with field tests. As can be seen from the graph, for the construction of a pedestrian bridge with a service life of 384 months (or 32 years), the curve of joint action is the closest, which confirms the adequacy of the proposed model.

6. Influence of the operational load on the degradation of structures under the combined action of carbonization and chloride aggression

Since 2011, RILEM TC 246-TDC (which includes five laboratories from different parts of the world) has developed a method for determining the strength of concrete [24] subjected to the combined effects of chloride penetration and mechanical stress.

In the course of this work, the scientists concluded that the diffusion coefficients tend to decrease with time of exposure, while the calculated surface concentrations increase. Thus, the data they obtained are in part consistent with the literature, which states that chloride diffusion occurs more slowly under moderate compressive loading, but increases if the applied load exceeds half of the ultimate load. The chloride content at the depth of the protective layer increases significantly when tensile stress is applied. This result was expected because the pore space or microcracks expand under tensile stress. Thus, the diffusion coefficient is calculated as follows:

$$D_{cl}(t) = k_e k_l D_{cl.0} \cdot (\frac{t_0}{t})^{ncl}$$

k_l – coefficient that takes into account the actual stress state of the structural element.

For various loading conditions, the stress coefficients k_l were calculated [24], in which k_l = 1 for the standard, k_l = 0.80 for loading (compression) 30 % of the ultimate breaking load, k_l = 1.17 for loading (compression) 60 %, k_l = 1.25 for loading (compression / tension) 50% and k_l = 1.53 for loading (tension) 80 %.

The service life of the elements loaded at 60 % of the compressive strength decreased by an average of 0.82 times in comparison with the unloaded elements. It should be noted that at a compressive stress ratio of 60 %, only two out of five laboratories found a noticeable increase in the diffusion coefficient (which is associated with a shortened service life), while others found a slight decrease in the diffusion coefficient. From the data presented by them [24], it can be concluded that further tests will be required in order to obtain more accurate information on the effect of operational loads on the service life of reinforced concrete elements. More research will be required to investigate the effect of operational loads on carbonation rate, however, some conclusions and adjustments to the cooperative model can be made now.

6. Conclusions

1. The analysis of the mechanism of corrosion destruction of shelf structures is carried out, the limiting state for the chemical reaction of chloride in the protective layer of concrete of shelf structures is formulated.
2. A model of degradation of the protective layer of concrete of coastal structures from the combined action of carbonization and chloride aggression is proposed.
3. The model was verified at the port facilities of the island. Sakhalin. The carried out field measurements of chloride penetration into concrete showed that at a depth of 50 mm, in the spray zone, the chloride concentration exceeds 0.4% of the cement weight (corrosion threshold) at a structure age of about 30 years.
4. The survey in the port of Kholmsk confirmed that locally, in certain cases, in the protective layer of concrete there are areas where the simultaneous action of both carbonization and chloride aggression is observed. In these local areas, the maximum concentration of chlorides is reached and reinforcement corrosion occurs. The service life of the surveyed structures did not reach the design service life.
5. Modeling the concentration of chlorine ions in the concrete of the protective layer in accordance with the accepted models, depending on the service life, climatic conditions and depth of reinforcement, made it possible to compare the chloride content at a certain depth when calculating with and without taking into account the combined effects of carbonization and chloride aggression.
6. The simulation results correlate well with field studies, which in the future will make it possible to develop effective ways to increase the durability and maintainability of structures operated in the marine environment.
7. The analysis of the influence of the operating load on the degradation of structures under the combined action of carbonization and chloride aggression is carried out, recommendations are given for changing the diffusion coefficient of chlorides.

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