

QUANTITATIVE DESIGN METHODS OF CORROSION PROTECTION THE REINFORCED CONCRETE STRUCTURES AT THE STAGES OF THE LIFE CYCLE

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ABSTRACT

Concrete and reinforced concrete are the main structural materials in modern construction. The area and volumes of application of these materials continues to expand. In recent years, in the practice of construction, there is a tendency to the use of structures that combine load-bearing and enclosing functions, as well as the functions of technological equipment. At the same time, their working conditions are becoming more complicated and harsh. In addition to the usual force effects (loads), structures are exposed to all kinds of environmental influences (actions) in the form of substances, energy, or a combination thereof.

According to current design standards in reinforced concrete structures designed to work in aggressive environments corrosion of materials is not allowed. However, there is a large amount of structures that have received corrosion damage at the operation stage.

The standards do not contain any guidelines for designing a parameters of the primary protection and repair system for reinforced concrete structures and their elements (durability forecast, repair period, determination of structural and technological parameters of the primary protection or repair systems).

Thus, there are tasks of designing the protection of reinforced concrete structures both at the design stage and at the operation stage. At the design stage, it is necessary to determine the structural and technological parameters of the primary protection that ensure the service life of structures or the period between repairs. At the stage of operation, it is necessary to determine the parameters of repair systems which provide the residual service life until the next repair or liquidation of reinforced concrete structures.

Our research shows the economic feasibility of designing reinforced concrete structures interacting with aggressive environment, taking into account the kinetics of concrete corrosion. The optimal design methods can be used to obtain the most economical solutions.

We have developed quantitative methodology for the design of primary protection of reinforced concrete structures.

INTRODUCTION

One of the most common effects on structures is aggressive effects, which are caused by the presence of natural or artificial aggressive environments in their origin. A number of industries in the chemical, metallurgical, light, food, pulp and paper and other industries use in the technological process or release substances that are aggressive towards building structures. According to the data of [1], from 6 to 70% of the total number of structures of structures in industry, and from 30 to 100% in agricultural production are exposed to aggressive environments.

Incorrect assessment of aggressive factors, the mismatch of the quality of concrete structures to the conditions of their work, and often underestimation of anti-corrosion measures by construction organizations or service departments, often lead to damage or complete failure of building elements.

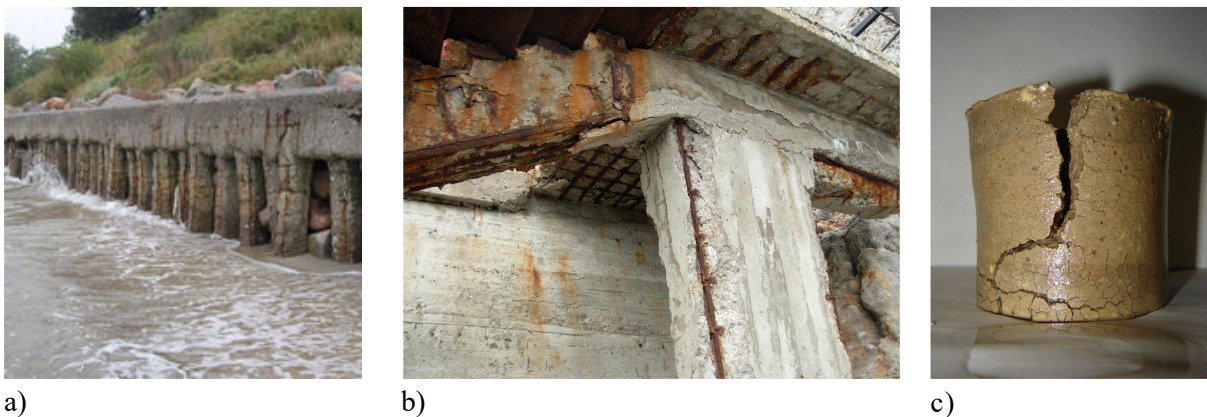


Figure 1. Corrosion damage to materials of reinforced concrete structures a) in sea water; b) in an airy seaside environment; c) concrete in a liquid aggressive environment when exposed to sulfates

According to the estimates of foreign experts, corrosion losses account for about 1.25% of the national income [1].

Thus, the need to expand research and study the behavior of concrete and reinforced concrete under the influence of aggressive environments is due to the requirements of comprehensive reduction of costs from corrosion of building structures.

QUANTITATIVE METHODOLOGY FOR THE DESIGN OF PRIMARY PROTECTION OF REINFORCED CONCRETE STRUCTURES

The following types of protection may be provided to prevent corrosion damage to concrete and reinforced concrete and structures [2]:

- 1) primary, consisting in the choice of constructive solutions, the material of the structure or in the creation of its structure in order to ensure the durability of this structure when used in an appropriate aggressive environment;
- 2) secondary, which consists in applying a protective coating, impregnating and applying other measures that limit or exclude the impact of an aggressive environment on concrete and reinforced concrete structures;
- 3) special, consisting in the implementation of technical measures not mentioned in lists 1) and 2), but allowing to protect concrete and reinforced concrete structures and materials against corrosion.

Primary protection measures include:

- 1) the use of concrete resistant to aggressive environments;
- 2) the use of additives that increase the corrosion resistance of concrete and their protective ability with respect to steel reinforcement, steel embedded parts and connecting elements;
- 3) decrease in permeability of concrete;

4) compliance with additional design and structural requirements when designing concrete and reinforced concrete structures.

When designing concrete and reinforced concrete structures intended for use in aggressive environments, durability should be provided mainly by primary protection means. The resistance of concrete is determined by such technological parameters as the mineralogical composition of cement clinker, the material composition of cement and the permeability of concrete. The chemical and mineralogical composition of cement clinker and the material composition of cement characterize the degree of chemical activity of cement stone, and permeability - the degree of accessibility of the inner surface of concrete.

The modern level of knowledge and the technique for monitoring the state of reinforcement excludes the possibility of taking any degree of corrosion of reinforcement or loss of adhesion to concrete (due to corrosion) in the calculation of the durability of structures. Therefore, the occurrence of the risk of reinforcement corrosion or loss of adhesion to concrete should be considered as a structural failure.

Thus, the calculation of the conditions for preventing corrosion of the reinforcement and the danger of the loss of the reinforcement adhesion to concrete includes the calculation of the amount of the introduced (removed) component of the aggressive medium (cement stone) or the products of their interaction (a new growth), which characterizes the accumulation (removal) in quantities that are dangerous from the point of view of corrosion reinforcement, the danger of the loss of the reinforcement adhesion to concrete or destruction of the concrete protective layer [3].

The protective layer or the technological parameters of the concrete of the protective layer ensure the failure-free life cycle of the reinforcement under condition (with a one-dimensional mass transfer process):

$$c_a(x = a_p, t) \leq c_{a,u} \quad (1)$$

$$y(t) \leq a_p \quad (2)$$

where: $c_a(x=a_p, t)$ - the amount of the introduced component of the aggressive medium (the removed component of concrete) or the introduced (taken out) product of their interaction (a new growth) at a depth equal to the value of the protective layer; $c_{a,u}$ - the maximum amount of an aggressive component (concrete component) or a new growth that can cause corrosion of reinforcing bars, extinguish passivating properties or soften (destroy) concrete; $y(t)$ - the penetration depth of the aggressive component, degeneration of the composition and structure of concrete in quantities hazardous to the safety of reinforcement; a_p - the value of the protective layer of concrete.

The main criteria that cause structural failure are accepted:

- a decrease in the alkalinity of the electrolyte surrounding the reinforcement to a pH equal to or less than 11.5 during carbonization or corrosion of concrete [1];
- achieving a concentration of chloride (Cl⁻) of 3 mg/l or sulfates - 800 mg/l on the surface of the reinforcement (critical concentration) [4];
- loss of concrete strength due to sulfate corrosion [3].

Structural and technological parameters provide the bearing capacity of structures – $R(t)$, which is compared with the external action – $F(t)$. The safety condition of load-bearing structures is written in the form:

$$R(t) \geq F(t) \quad (3)$$

Mass transfer theory describes the spatio-temporal distribution of the concentration of a substance, as well as mass flows. The phenomena of transfer are based on the fundamental laws of conservation and conversion of energy. Based on these laws, the most general mass transfer equations are obtained [298]. A quantitative description of mass transfer in general form includes a description of diffusion due to the concentration gradient of the substance, a description of the transfer due to the action of temperature (thermal diffusion), force (pressure), humidity, and other fields, and also takes into account the chemical interaction of the components of the medium and materials.

In the practice of engineering calculations, usually the cross effects (thermal diffusion, barodiffusion) have little effect on mass transfer; therefore, they are usually not taken into account in analytical solutions to mass transfer problems.

The process of unsteady one-dimensional diffusion complicated by a chemical reaction is described by a differential equation obtained on the basis of Fick's second law:

$$\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2} \pm kc^\alpha, \quad (4)$$

where: c - concentration; t - time; D - the diffusion coefficient; x - coordinate; k - chemical reaction constant; α - reaction order; signs indicate the addition or decrease of chemical reaction components.

The effective diffusion coefficient characterizes the permeability or degree of accessibility of the inner surface of concrete. Its value is a function of the structure of concrete and, therefore, all factors affecting the structure: the quantity and quality of the starting components, particle size distribution of aggregates, water-cement ratio, hardening conditions, degree of hydration of cement stone, etc. A significant effect on the spatio-temporal change in the structure of concrete has gradient stress state and the process associated with the accumulation of new growth. In addition, the diffusion coefficient is a function of temperature. Thus, in general terms, the effective diffusion coefficient is a complex function of the form:

$$D = D[C, S, G, p_j, W / C, p_i, \alpha_g, \sigma(x, t), c_{ab}(x, t), T] \quad (5)$$

where: C, S, G - accordingly, the quantity of cement, fine and coarse aggregates in concrete; W/C - water-cement ratio; p_i - hardening parameters; p_j - parameters characterizing the quality of the initial components of concrete; α_g - hardening parameters; $\sigma(x, t)$ - stress; $c_{ab}(x, t)$ - the quantity (concentration) of a new growth; T - the temperature.

The chemical reaction rate constant characterizes the degree of activity of the inner surface of a cement stone. The research results show that the most significant factors affecting its size are: the chemical and mineralogical composition of cement (the amount of C_3S, C_2S, C_3A, C_4AF , gypsum, active additives, etc.), the amount of active fillers or aggregates, pH of the medium, type and concentration of concomitant ions in a multicomponent system of an aggressive environment, temperature, etc. Therefore, the rate constant of chemical reactions can be written as a function:

$$k = k[n(C_3S), n(C_2S), n(C_3A), n(C_4AF), n(CaSO_4), n(A), n(Ag), pH, c_i, T] \quad (6)$$

where: $n(C_3S), n(C_2S), n(C_3A), n(C_4AF), n(A)$ - accordingly, the amount of C_3S, C_2S, C_3A, C_4AF , gypsum, active additives in cement; $n(Ag)$ - the amount of active fillers or aggregates in concrete; pH - pH of the medium; c_i - type and concentration of concomitant ions; T - temperature.

Taking into account expressions (5) and (6), as well as inconstancy of the diffusion coefficient, equation (4) will take the form:

$$\frac{\partial c_a}{\partial t} = \frac{\partial}{\partial x} \left\{ D_a [C, S, G, p_j, W / C, p_i, \alpha_g, \sigma(x, t), c_{ab}(x, t), T] \frac{\partial c_a}{\partial x} \right\} \pm k [n(C_3S), n(C_2S), n(C_3A), n(C_4AF), n(CaSO_4), n(A), n(Ag), pH, c_i, T] c_a^\alpha \quad (7)$$

Equation (7) describes the spatio-temporal distribution of an aggressive medium in concrete during a one-dimensional mass transfer process. However, the change in the properties of concrete in general is determined not only by the amount of aggressive medium entering the concrete, but also by the number of hydrated formations (active components of concrete) that determine the strength of the cement stone, as well as the

number of interaction products (a new growth). In this case, it is also necessary to supplement equation (7) with equations describing the spatiotemporal distribution of the active components of concrete and their interaction products. Independent equations should be written for them, and the number of equations becomes equal to the number of components that must be taken into account.

In general, the mass transfer process is not one-dimensional. The noted features of the mass transfer process are described by a system of equations of the form:

$$\frac{\partial c_{a,i}}{\partial t} = \sum_{j=1}^N \frac{\partial}{\partial x_j} \left[D_{a,i}(S, T, \sigma, c_{ab,k}, \dots) \frac{\partial c_{a,i}}{\partial x_j} \right] - k_{il}(H, T, \sigma, \dots) \prod_{i=1}^M c_{a,i}^{\alpha_i} \prod_{l=1}^L c_{b,l}^{\beta_l} \quad (8)$$

$$\frac{\partial c_{b,l}}{\partial t} = \sum_{j=1}^N \frac{\partial}{\partial x_j} \left[D_{b,l}(S, T, \sigma, c_{ab,k}, \dots) \frac{\partial c_{b,l}}{\partial x_j} \right] - \varkappa_{b,l} \varphi k_{il}(H, T, \sigma, \dots) \prod_{i=1}^M c_{a,i}^{\alpha_i} \prod_{l=1}^L c_{b,l}^{\beta_l} \quad (9)$$

$$\frac{\partial c_{ab,k}}{\partial t} = \sum_{j=1}^N \frac{\partial}{\partial x_j} \left[D_{ab,k}(S, T, \sigma, c_{ab,k}, \dots) \frac{\partial c_{ab,k}}{\partial x_j} \right] + \varkappa_{il} k_{il}(H, T, \sigma, \dots) \prod_{i=1}^M c_{a,i}^{\alpha_i} \prod_{l=1}^L c_{b,l}^{\beta_l} \quad (10)$$

where: $c_{a,i}$, $c_{b,l}$, $c_{ab,k}$ - accordingly, concentration of the i -th active component of an aggressive environment; l -th active component of concrete k -th product of interaction; $D_{a,i}(S, T, \sigma, c_{ab,k}, \dots)$, $D_{b,l}(S, T, \sigma, c_{ab,k}, \dots)$, $D_{ab,k}(S, T, \sigma, c_{ab,k}, \dots)$ - effective diffusion coefficients of the i -th component of the aggressive medium, the l -th component of concrete, the k -th interaction product; the l -th component of concrete, the k -th interaction product; $k_{il}(H, T, \sigma, \dots)$ - the rate constant of the chemical reaction of the i -th component of the aggressive environment and the l -th active component of concrete; $\varkappa_{b,l}$, \varkappa_{il} - stoichiometric coefficient; S - structural parameters of concrete; H - characteristics of the chemical activity of concrete; T - temperature; σ - stresses; x_j - spatial coordinates; t - time.

To solve the differential equations of mass transfer, it is necessary to specify boundary conditions that include the initial and boundary conditions.

The initial conditions are set as a function of the coordinates of the concentration distribution at time equal to zero:

$$c_{a,i}(x_j) = c_{a,i}(x_j)_{t=0} \quad (11)$$

The boundary conditions are usually divided into four types. The boundary conditions of the first kind are to set the concentration at any time on the surface of the body:

$$c_{a,i}(t) = c_{a,i}(t)_{x_j=0} \quad (12)$$

The boundary conditions of the second kind consist in setting the density of mass flows at each point on the surface of the body, as a function of time:

$$q(t) = q(t)_{x_j=0} \quad (13)$$

The boundary conditions of the third kind are to set the concentration of the environment and the law of mass transfer between the surface of the body and the environment:

$$D_{a,i} \left(\frac{\partial c_{a,i}}{\partial x_j} \right)_{x_j=0} + \alpha \left[c_{a,i}(t)_{x_j=0} - c_{a,i}(t)_{x_j=-\infty} \right] = 0 \quad (14)$$

where: α - mass transfer coefficient; $c_{a,i}(t)_{x_j=0}$, $c_{a,i}(t)_{x_j=-\infty}$ - accordingly, the concentration of the substance on the surface of the body and in the environment.

The boundary conditions of the fourth kind correspond to the ideal contact of the surfaces of two bodies. In this case, at the contact boundary, equal concentrations of the substance should be ensured, as well as equality of diffusion fluxes:

$$c_{a,i}(t)_{1,x_j=0} = c_{a,i}(t)_{2,x_j=0}, \quad D_{a,1} \left(\frac{\partial c_{a,i}}{\partial x_j} \right) = D_{a,2} \left(\frac{\partial c_{a,i}}{\partial x_j} \right) \quad (15)$$

The proposed system of equations (8) ... (10) together with the boundary conditions (11) ... (15) allows one to take into account all the most important features of the concrete corrosion process during diffusion complicated by chemical reactions: multicomponent aggressive environment; parallelism of chemical reactions; the dependence of the permeability of concrete on the initial characteristics of the structure, stress state, temperature, the degree of development of the corrosion process; the dependence of the chemical reaction rate constant on the chemical-mineralogical and material composition of cement, the type and concentration of accompanying ions in a multicomponent system of an aggressive environment, temperature; multidimensionality of the process (the ability to consider bodies of any shape and volume); change in the concentration of the external aggressive environment in time according to any law.

Based on the proposed kinetic dependences of the corrosion processes(4)...(15) and safety condition (1)...(3), it is possible to solve the problems of evaluating the durability of concrete of the protective layer, regulating the technological parameters of concrete and the value of the protective layer that provide a given service life.

CONCLUSIONS

1. One of the most common effects on reinforced structures is aggressive effects, which are caused by the presence of natural or artificial aggressive environments in their origin. There is a large amount of structures that have received corrosion damage at the operation stage.
2. When designing concrete and reinforced concrete structures intended for use in aggressive environments, durability should be provided mainly by primary protection means. Eurocodes and National standards do not contain any guidelines for designing a parameters of the primary protection and repair system for reinforced concrete structures and their elements (durability forecast, repair period, determination of structural and technological parameters of the primary protection or repair systems).
3. For the first time, the system of equations is formulated, which describes diffusion complicated by chemical reactions. Together with the boundary conditions, the equations allow one to take into account the most important features of the concrete corrosion process.
4. Safety conditions for reinforcement are formulated based on the condition of preventing its corrosion or loss of adhesion to concrete, as well as the condition of reliability of load-bearing reinforced concrete structures
5. Based on the proposed kinetic dependences of the corrosion processes and safety condition, it is possible to solve the problems of evaluating the durability of concrete of the protective layer, regulating the technological parameters of concrete and the value of the protective layer that provide a given service life.

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