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QUANTITATIVE DESIGN METHODS FOR PROTECTION AGAINST CORROSION OF REINFORCED CONCRETE STRUCTURES DURING VARIOUS STAGES OF THEIR LIFE CYCLE

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Abstract

There are large amounts of reinforced concrete structures that have undergone damage from corrosion at their operational stage. The Eurocodes and national standards do not contain any guidelines for designing primary protection and repair systems for reinforced concrete structures. Our research shows the economic feasibility of designing reinforced concrete structures that can interact with an aggressive environment, taking into account the kinetics of concrete corrosion. Optimal design methods can be used to obtain the most economical solutions. We have developed a quantitative methodology for the design of the primary protection of reinforced concrete structures.

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Key words

- Reinforced concrete structures,
- Concrete corrosion,
- Primary protection, Mass transfer process,
- Safety conditions.

1 INTRODUCTION

Concrete and reinforced concrete are the main structural materials in modern construction. The areas and volumes of the application of these materials continue to expand. In recent years, there is a tendency in the construction practice to use 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 (Alexander et al., 2017)

One of the most common effects on structures is the effect of corrosion, which is caused by natural or artificial aggressive environments. A number of companies in the chemical, metallurgical, light, food, pulp and paper, and other industries use or release substances that are aggressive towards building structures in the technological process. According to the data of (Moskvin et al., 1980), from 6 to 70% of the total number of structures in industry and from 30 to 100% in agricultural production are exposed to aggressive environments.

According to current design standards for reinforced concrete structures designed to work in aggressive environments, the corrosion of materials is not allowed. Incorrect assessments of aggressive factors, mismatches between the quality of concrete structures and their working conditions, and often the underestimation of anti-corrosion measures by construction organizations or service departments often lead to the damage or complete failure of building elements. Therefore, it is necessary to devise the protection of reinforced concrete structures both at the design stage and at the operational stage. At the design stage, it is necessary to determine the structural and technological parameters of the primary protection that can ensure the service life of structures or periods between repairs. At the operational stage, it is necessary to determine the parameters of repair systems that can provide residual service life until the next repair or liquidation of reinforced concrete structures.

According to the estimates of international experts, losses due to corrosion account for about 1.25% of national income (Moskvin et al., 1980).

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

2 METHODS USED

Damage to reinforced concrete structures that are operated in aggressive environments is caused by the development of corrosive processes in the protective layer of the concrete. Studies have described the process of the corrosion of reinforced concrete structures when exposed to liquid aggressive environments.

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Fig. 1 *Corrosion damage to materials of reinforced concrete structures: a) in seawater; b) in a windy seaside environment; c) concrete when exposed to sulfates*

The protective and strength properties of concrete depend on the quantitative characteristics of the corrosion process, i.e., the amount of the introduced (removed) component of the aggressive medium (cement stone) or the products of their interaction (new growth).

The theory of mass transfer is used to describe corrosion fields in a multidimensional diffusion that is complicated by heterogeneous chemical reactions. Together with the boundary conditions, the equations of mass transfer allow the most important features of the concrete corrosion process to be taken into account.

Safety conditions for reinforced concrete structures are formulated according to reliability of the bearing capacity and operability of the protective layer.

The quantitative technique developed in this study allows for the reasonable assignation of the parameters of the primary protection of reinforced concrete structures for the stages of the life cycle, i.e., design or repair.

3 METHODOLOGY

The following types of protection may be provided to prevent damage from corrosion to concrete and reinforced concrete structures (State standard of Ukraine B.2.6-145, 2010):

1) primary: consists of a choice of constructive solutions, the material of the structure or 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 of applying a protective coating and impregnating and applying other measures that limit or exclude the impact of an aggressive environment on concrete and reinforced concrete structures;
3) special: consists of the implementation of technical measures not mentioned in 1) and 2) above, which can 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 resistance to corrosion of concrete and their protective ability with respect to steel reinforcement and steelembedded parts and connecting elements;
3) decrease in the 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 mainly be provided by means of primary protection. The Eurocodes (fib, 2006), (Gehlen, 2007) and national standards (State standard of Ukraine B.2.6-145, 2010) do not contain any guidelines for designing primary protection.

The resistance of concrete is determined by such technological parameters as the mineralogical composition of the cement clinker, the material composition of the cement, and the permeability of the concrete. The chemical and mineralogical composition of cement clinker and the material composition of cement characterize the degree of the chemical activity of cement stone and the permeability, i.e., the degree of accessibility of the inner surface of the concrete.

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

Thus, the calculation of the conditions for preventing the corrosion of the reinforcement and the danger of the loss of the adhesion of the reinforcement to the concrete include the calculation of the amount of the introduced (removed) component of the aggressive medium (cement stone) or the products of their interaction (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 adhesion of the reinforcement to the concrete or the destruction of the concrete's protective layer (Savytskyi, 1994).

With a one-dimensional mass transfer process, the protective layer or the technological parameters of the concrete of the protective layer ensure a failure-free life cycle of the reinforcement given that:

$$c_a(x=a_p,t)<c_{a,t} \tag{1}$$

$$y(t)<a_p \tag{2}$$

where $c_a(x = a_p,t)$ - the amount of the introduced component of the aggressive medium (the removed component of the concrete) or the introduced (taken out) product of their interaction (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 new growth that can cause corrosion of reinforcing bars, extinguish passivating properties or soften (destroy) concrete;

$y(t)$- the depth of penetration of the aggressive component, or degeneration of the composition and structure of the concrete in quantities hazardous to the safety of the reinforcement;

a_p - the value of the protective layer of the concrete.

The main criteria that can cause structural failure are accepted as:
- a decrease in the alkalinity of the electrolytes surrounding the reinforcement to a pH equal to or less than 11.5 during carbonization or corrosion of the concrete (Moskvin et al., 1980);
- achieving a concentration of chloride (Cl-) of 3 mg/l (Poulsen et al., 2006) or of sulfates of 800 mg/l on the surface of the reinforcement (critical concentration) (Alekseev et al., 1990);
- loss of the strength of the concrete due to sulfate corrosion (Savytskyi, 1994).

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

$$R(t) \geq F(t) \tag{3}$$

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 (Savytskyi, 1994). A quantitative description of mass transfer in a 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 the temperature (thermal diffusion), force (pressure), humidity, and other fields; it 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:

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

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 the chemical reaction components.

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

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

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

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

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

where:
$n(C_3S),\ n(C_2S),\ n(C_3A),\ n(C_4AF),\ n(A),$ i.e., the amount of C_3S, C_2S, C_3A, C_4AF, gypsum, active additives in the cement;
$n(Ag)$ - the amount of active fillers or aggregates in the 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 the inconstancy of the diffusion coefficient, equation (4) will take the form:

$$\frac{\partial c_a}{\partial t} = \frac{\partial}{\partial x}\left\{D_a\left[C,S,G,p_j,W/C,p_i,\alpha_g,\sigma(x,t),c_{ab}(x,t),T\right]\frac{\partial c_a}{\partial x}\right\} \pm \tag{7}$$

$$\pm\, k\left[n(C_3S),n(C_2S),n(C_3A),n(C_4AF),n(CaSO_4),n(A),n(Ag),pH,c_i,T\right]c_a^{\alpha}$$

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 the aggressive medium entering the concrete, but also by the number of hydrated formations (active components of the concrete) that determine the strength of the cement stone, as well as the number of interaction products (new growth). In this case, it is also necessary to supplement equation (7) with equations describing the spatiotemporal distribution of the active components of the concrete and their interaction products. Independent equations should be written for these components, 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 in the form:

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

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

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

where:
$c_{a,i}$, $c_{b,l}$, $c_{ab,k}$, i.e., the concentration of the i-th active component of an aggressive environment; l-th, the active component of the concrete; and k-th, the product of the interaction;

$D_{a,i}(S,T,\sigma,c_{ab,k},...)$, $D_{b,l}(S,T,\sigma,c_{ab,k},...)$, $D_{ab,k}(S,T,\sigma,c_{ab,k},...)$, i.e., the effective diffusion coefficients of the *i*-th component of the aggressive medium, the l-th component of the concrete, the k-th interaction product;

$k_{il}(H,T,\sigma,...)$ – the rate constant of the chemical reaction of the *i*-th component of the aggressive environment and the *l*-th active component of the concrete;

$æ_{b,l}$, $æ_{il}$ – stoichiometric coefficient;

S – structural parameters of the concrete;

H – characteristics of the chemical activity of the concrete;

T – temperature;

σ – stresses;

x_j – spatial coordinates;

t – time.

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

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

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

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:

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

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

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

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:

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

where: α- mass transfer coefficient;

$c_{a,i}(t)_{xj=0}$, $c_{a,i}(t)_{xj=-\infty}$ - i.e., 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 the two bodies. In this case, equal concentrations of the substance at the contact boundary should be ensured, as well as the equality of the diffusion fluxes:

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

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, as complicated by the chemical reactions: a multicomponent aggressive environment; the parallelism of the chemical reactions; the dependence of the permeability of the concrete on the initial characteristics of the structure; the stress state; the temperature; the degree of the development of the corrosion process; the dependence of the chemical reaction rate constant on the chemical-mineralogical and material composition of the cement; the type and concentration of the accompanying ions in a multicomponent system of an aggressive environment; the temperature; the multidimensionality of the process (the ability to consider bodies of any shape and volume); and the changes in the concentration of the external aggressive environment over time according to any law.

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

Based on the proposed methodology, the optimal design methods can be used to obtain the most economical solutions for the primary protection of reinforced concrete structures.

4 CONCLUSIONS

1. One of the most common effects that occur to reinforced structures is aggressive effects that are caused by the presence of natural or artificial aggressive environments. There are large amounts of structures that undergo corrosive damage at the operational stage.
2. When designing concrete and reinforced concrete structures intended for use in aggressive environments, durability should mainly be provided by means of primary protection. Eurocodes and national standards do not contain any guidelines for designing parameters for primary protection and repair systems for reinforced concrete structures and their elements (durability forecasts, repair periods, or determination of the structural and technological parameters of the primary protection or repair systems).
3. For the first time, a system of equations has been formulated that describes diffusion complicated by chemical reactions. Together with the boundary conditions, the equations allow the most important features of the concrete corrosion process to be taken into account.
4. The safety conditions for reinforcements are formulated based on preventing corrosion or the loss of adhesion to the concrete, as well as the reliability of load-bearing reinforced concrete structures
5. Based on the proposed kinetic dependences of the corrosion processes and safety conditions, it is possible to solve problems of evaluating the durability of the concrete of the protective layer and regulating the technological parameters of the concrete and the value of the protective layer that provide a given service life.
6. Based on the proposed methodology, there are more cost-effective solutions available for the primary protection of reinforced concrete structures.

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