Analysis of factors affecting the performance of reinforced concrete structures of engineering constructions under the influence of aggressive environment

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Abstract: The work is devoted to the study of the performance of reinforced concrete structures of engineering structures operating under the synergetic influence of aggressive environment with damage to concrete and main reinforcement.

1. Introduction
During health ensuring of reinforced concrete structures engineering structures should be ensured by both technological and constructive requirements. When exposed to aggressive environments, it is necessary to protect building structures from corrosion and it is one of the main and big problems in addressing the issue of ensuring the durability of buildings and structures.

One of the main causes of reinforced concrete structures of engineering constructions corrosion is the impact of aggressive environments of man-made and natural character. This leads to active destructive processes. It is well known that the change of material properties in time depends on the interaction with the environment and is irreversible. Especially clearly destructive processes are observed in areas of variable water level, active chemical and physical effects of the environment. For example, in the construction of industrial hydraulic engineering (hyperbolic tower cooling towers, fan cooling towers, air tanks, filters, settling tanks, dock chambers, gravity embankments). During the operational period of 6-8 years, the depth of corrosion of concrete reaches 8-10 cm, and for the period of 25-30 years can reach 1-1.5 m. In addition, as the aggressive environment penetrates, the bodies of the structure, the protective properties of the concrete decrease with respect to the reinforcement, which begins to corrode. All this affects the bearing capacity of reinforced concrete structures [1].

Thus, when considering the corrosion of reinforced concrete, it is possible to determine synergistic effects, such as the combined action of the external environment (high humidity, temperature, etc.), aggressive environment (various liquids, gases, solid aggressive formations), taking into account the stress-strain state of the reinforced concrete element [1-3].

2. The synergistic effects of environments on the concrete properties
Synergetic effects of environment lead to significant changes in the deformation and strength properties of concrete affected area. The change in material properties over time is irreversible and depends on the deformation conditions and the interaction with the environment. In addition, as the aggressive environment penetrates into the body of the structure, the protective properties of the
concrete decrease with respect to the reinforcement, which begins to corrode. As a result of corrosion, the cross-sectional area of the reinforcement decreases and its adhesion to concrete is broken. All this affects the bearing capacity of reinforced concrete structures.

Damages of concrete are noted at action on it of water solutions of acids or acid gases, solutions of salts and even alkalis, some organic compounds. The degree of aggressive action depends not only on the composition of the aggressive environment, but also on the contact conditions, the speed and pressure of the liquid environment, the density of the adjacent soil under the action of groundwater, the temperature of the environment, power loads, the stress state of the material of structures and other factors. Almost all the effects that occur with the participation of aggressive solids and gases can be attributed to synergistic, since the presence of water is necessary for the chemical reaction under normal conditions. All acidic gases acting on the concrete structures, together with the CO₂. In most cases, the advanced process is the carbonation of concrete, which begins with the manufacture of the structure, while specific acidic gases begin to act, as a rule, only after the start of operation of the building. The effect of gases on the concrete causes its neutralization, and the resulting salts penetrate deep into the concrete at a rate depending on their solubility, permeability and humidity [4].

The nature of the main destructive processes is presented in table 1.

| Environment                          | Environmental exposure conditions | Predominant processes in concrete                      |
|--------------------------------------|----------------------------------|-------------------------------------------------------|
| Air-wet                              | Free-flow                        | Neutralization                                        |
|                                      | Pressured                        | Same, accelerated                                      |
| Air-wet, with the presence of solutions of salts, acids, etc. and with direct periodic humidification | Free-flow                        | Increase in the amount of introduced aggressive components or products from interaction with cement stone, neutralization, diffusion of aggressive ions |
|                                      | Pressured                        | The same processes, accelerated +leaching              |
| Aqueous with the presence of solutions of salts, acids, etc. | Free-flow                        | Diffusion of aggressive ions                           |
|                                      | Pressured                        | The same leaching                                      |

3. Mathematical model of concrete corrosion

To assess the corrosion damage of concrete in reinforced concrete structures of engineering structures, the following indicators can be used: the depth of damage to concrete and service life.

It is obvious that the ultimate goal of constructing a mathematical model of corrosion $L=f(t)$ is to obtain a simple formula, which is convenient to perform engineering calculations. However, almost all researchers in the derivation of the dependence $L=f(t)$ to simplify proceed from the interaction of only two substances.

As a result of the study of the methodical approach to the determination of the service life of concrete and the preparation of proposals for the quantitative assessment of the kinetics of corrosion processes arising from the contact of liquid corrosive environment with concrete, which were based on the analysis of the nature of corrosion processes, the following conclusions were obtained in the works of domestic authors [1, 5]:

- it is established that the intensity of corrosion processes is determined by the intensity of penetration of aggressive components of the environment into the pore structure of concrete;
- the movement of the aggressive environment from the outer surface deep into the concrete is carried out under the influence of hydrostatic pressure, molecular diffusion and capillarity; the pressure of the external environment on the open surface of the concrete accelerates this process;
- such classification of the acting forces inducing movement of the aggressive environment in concrete allows for stationary conditions to carry out quantitative calculations of a stream of
aggressive substance through a concrete surface and to give an assessment of its influence on a condition of concrete in time for simple boundary conditions.

**Table 2.** Characterization of the synergistic interaction of the two substances.

| Examples of the interaction of concrete with a diffusing external environment | Description process’s | Differential equation, describing the process [2] |
|---|---|---|
| Contact of cement stone with solutions of salts, acids, etc. | The presence of chemical interaction of concrete with the environment, the process is controlled by diffusion and chemical reaction. Dissolution of cement stone minerals, enhanced by the action of acids. The accumulation in the concrete pores of salts that are able to switch into other crystalline hydrate forms with a volume change. Destruction of aggregate contacts with cement stone. | 

\[
\begin{align*}
\frac{\partial c_A}{\partial t} &= D_A \cdot \frac{\partial^2 c_A}{\partial x^2} + RC_i \\
\frac{\partial c_B}{\partial t} &= D_B \cdot \frac{\partial^2 c_B}{\partial x^2} + \frac{k_p\sigma}{\nu_g} R(C_i)
\end{align*}
\]  

(1) |
| Contact of cement stone with chlorides | The absence of chemical interaction of concrete with the environment, the process is controlled by diffusion. The formation of gypsum with a significant volume increase. | \[
\frac{\partial c_A}{\partial t} = D_A \cdot \frac{\partial^2 c_A}{\partial x^2}
\]  

(2) |

Corrosion of concrete in the product or structure is caused by the activity of organisms. Biological corrosion is most common in those structures where organic substances come into contact with the surface of reinforced concrete. Corrosion destruction is accompanied by leaching of calcium and magnesium in the form of sulphates from concrete [2].

4. Influence of environment aggressiveness on the loss of bearing capacity of structures

Climatic effects on concrete, which include temperature, humidity, the number of transitions through 0°C, destroy the surface structure of its layers, lead to the formation of closed microcracks, which connecting with each other, form a through porous system, facilitating access to subsequent effects of chloride ions or carbon dioxide.

The General theory of the processes occurring during the freezing of water-saturated concrete is still in the stage of its development. Features of the destruction process during freezing of water-saturated concrete are reflected in the works of V. M. Moskvin, V. B. Gusev, N. K. Rosenthal and other authors [6-8]. The movement of the freezing front and the increase in volume during the phase transition to ice causes the movement of water. At the same time, the pore pressure increases sharply, which reduces the crystallization temperature. In the presence of salt solutions in the liquid phase of concrete it is affected by the concentration of salt solutions [3]. The practice of surveys shows that one of the main reasons for reducing the bearing capacity of reinforced concrete structures is the influence of aggressive environmental influences. The most unfavorable result of this effect is the chemical corrosion of reinforced concrete. In industrialized countries, corrosion damage is estimated at 3-5 % of gross national income, with 13-19 % of building structures. Currently, the effect of corrosion on the bearing capacity of reinforced concrete structures during the survey is estimated [9-11].

Thus, in the surface layers of concrete in contact with the external environment, under the action of carbonic and hydrochloric acids and magnesia salts, the structural elements of hydrated cement stone and sometimes non-hydrated grains of cement clinker are destroyed. New formations do not
possess astringent properties and sufficient density to inhibit further penetration of the aggressive environment. They are washed off; dissolved and deeper concrete layers are exposed.

Aggressive factors causing the destruction of reinforced concrete structures are: the dissolving ability of water, the content of hydrogen ions, the content of salts and sulfates, the alkali content, acids and direct current flow, biodeterioration of concrete by microorganisms. The degree of their aggressive effect on concrete determined in accordance with the requirements of GOST 31384 [12] and SP 28.13330 [13].

The degree of aggressiveness of the medium and the depth of destruction of the surface layer of concrete, affecting the loss of the bearing capacity of concrete structures, are presented in table 3 [13]. With the simultaneous exposure of various aggressive environments, the degree of exposure of the medium to concrete is determined by the more aggressive considering the operating conditions of the structure [13].

Table 3. Loss of bearing capacity in the operation of structure.

| The degree of aggressiveness of the environment | Depth of destruction of the surface layer (mm/year) | Average annual loss of bearing capacity in the operation of structures (%) |
|-----------------------------------------------|-----------------------------------------------|---------------------------------------------------------------------|
| Weak                                          | up to 0.4                                     | 3                                                                   |
| Average                                       | 0.4-1.2                                       | 5                                                                   |
| Strong                                        | More than 1.2                                 | 8                                                                   |

Table 4. The degree of aggressiveness of the environment.

| The degree of aggressiveness of the environment | Corrosion damage, (mm/year) | Points by GOST 13819-68 [11] | Decrease in strength in the area of corrosion (%) |
|------------------------------------------------|-----------------------------|-------------------------------|-----------------------------------------------|
| Nonaggressive                                   | 0.1                         | 1-3                           | 0                                             |
| Weak                                           | 0.01-0.05                    | 4.5                           | up to 5                                       |
| Average                                        | 0.05-0.5                     | 6                             | up to 10                                      |
| Strong                                         | >0.5                         | >7                            | >10                                           |

Evaluation of the life of the operating structures is proposed to perform by formula (3):

$$t_{sp} = \frac{t_{od} \cdot \delta^2}{(m_1 \cdot x_{od})^2} - t_{od},$$ (3)
where $t_{об}$, $t_{пр}$ is taken accordingly, the service life of the structure at the time of the survey and the projected service life (resource), $x_{об}$ – depth of concrete carbonation at the time of the survey.

5. Summary
Currently there are different approaches various approaches to assessing the corrosion damage of concrete and fittings. In relation to the definition of reinforced concrete structures performance subject to synergistic effects of the media, it is recommended to apply the following criteria for assessing the state of a reinforced concrete element: depth of corrosion damage to concrete; decrease in concrete strength; assessment cumulative valve damage reinforced concrete structures.

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