Life time of Reinforced Concrete floors of industrial buildings, connected with the use of chlorine

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Abstract. The article deals with the issues of durability (Life time) of floors of industrial buildings associated with the presence of chlorine. It is shown that, together with carbon dioxide, chlorine forms well-soluble hygroscopic layers in the form of calcium chloride. The movement of chlorine salts causes corrosion of the reinforcement and penetrates deep into the concrete. Therefore, the service life of reinforced concrete elements when exposed to an external aggressive environment is reduced due to corrosion of reinforcement and concrete. Experimental data and analytical dependences of the advance of the front of chloride concentrations dangerous for reinforcement and destruction of concrete under the action of the considered aggressive environment are presented. A formula is derived for the design service life of reinforced concrete structures by the factor of the passivating action of the protective layer of concrete. An empirical dependence of the service life of the structure on the depth of corrosion (diameter reduction) of the reinforcement was also obtained. The coefficient of corrosive wear of reinforcement for rectangular and tee sections bending reinforced concrete elements is calculated.

1 Introduction

The air environment of buildings and structures of industrial enterprises for the production of nickel and cobalt, containing chlorine, aggressively affects reinforced concrete structures, in particular, floors, causing their accelerated wear [1]. Corrosion is one of the main and common causes of significant destruction in Reinforced Concrete structures.

It is known that chlorine acts on concrete together with carbon dioxide. When chlorine interacts with calcium hydroxide and carbonate, well-soluble hygroscopic layers are formed in the form of calcium chloride, hypochlorite and their derivatives, tricalcium hydrochloraluminate and hydrochloroferrite. Basic compounds and hypochlorite, which are stable in the presence of calcium hydroxide, are decomposed by carbon dioxide.

The resulting solution of calcium chloride due to diffusion and capillary suction gets deep into the concrete. As a result of the transition of a significant part of the solid phase of cement stone into a saline solution, the surface layer of concrete becomes more porous and collapses.

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The movement of chlorine salts, which cause reinforcement corrosion, deep into the concrete occurs faster than the carbonization front, and the reinforcement corrodes in an alkaline environment [2, 3]. The increase in the volume of corrosion products of reinforcing steel contributes to the destruction of the protective layer of concrete. Cracks form in the protective layer along the reinforcing bars, concrete spalls.

As you know, the service life of reinforced concrete elements when exposed to an external aggressive environment is reduced due to corrosion of reinforcement and concrete. Currently, ongoing experimental, numerical and theoretical studies confirm the need to study such structures. In one of these works [4], experimental studies of six reinforced concrete beams for fatigue loads were performed.

The bearing capacity of corrosion-damaged beams and beams additionally exposed to moisture in a 5% NaCl solution decreased by 56% and 60%, respectively, and in chloride-containing beams by 78%.

In [5], experimental studies of a reinforced concrete beam with prestressing reinforcement were carried out.

In addition to reducing the cross section of corrosion-damaged rods, there is a problem of assessing the adhesion of such rods to concrete. In [6], a numerical assessment was made of the adhesion of corrosion-damaged rods to concrete in bending beams. The authors proposed to use nine parameters that characterize the relationship of corrosion-damaged reinforcement with concrete. It was determined that the partial absence of a protective layer of concrete leads to a significant decrease in the adhesion forces, and it practically did not affect the opening of cracks in the tension zone. Corrosion of steel reinforcement can lead to such significant damage to reinforced concrete structures that it will be impossible to restore. As the steel bar corrodes, the cross-sectional areas of the reinforcing bars decrease and corrosion products (rust) of greater volume surround the steel reinforcement.

Rust has a tensile effect on the surrounding concrete, causing radial cracks. Consequently, the bond stress between steel reinforcement and concrete will deteriorate [7].

The corrosion facility consisted of an anode electrode, a cathode electrode, an electrolyte vessel, a DC power supply, a logging device, and a corrosion bath. A low concentration solution was used to achieve uniform corrosion [8].

A similar method has been used to accelerate corrosion in various studies [9].

Therefore, it is recommended to take into account the concrete cover when choosing the applied current in order to achieve the planned weight loss of the reinforcement. This conclusion was reached in [10].

The frequency response can be used as a criterion for evaluating reinforced concrete elements [11].

Also in [12,13] the issues of reliability of a reinforced concrete slab with corroded reinforcement are considered from the standpoint of a probabilistic calculation.

In [14] experimental studies of eccentrically compressed locally corrosion-damaged reinforced concrete columns were carried out under a longitudinal dynamic load. Based on the results of the research, it was determined that the deformation diagrams in sections with impaired adhesion of tensile reinforcement to concrete fundamentally differ in shape from the deformation diagrams in sections of undamaged elements. The height of the compressed zone of concrete changes significantly, so at 25% corrosion damage to the tensile reinforcement, the value of the height of the compressed zone will decrease by 75%.

2 Methods

In order to establish the durability of structures, beams and slabs of reinforced concrete floors of such industrial buildings with a service life of years were examined, located at an air temperature of 18-35°C, a humidity of 56-87% with a chlorine concentration in the air of 1-20 mg/m³ [15,16,17]. According to [18], such a medium is highly aggressive. The structures were made of concrete on medium aluminate Portland cement of classes B12.5-B20, the water
resistance grade is lower than the required one [18] - W2-W4. Reinforcement of a smooth and periodic profile A240 and A400 with a diameter of 14-36mm; reinforcement of elements with a single-row arrangement of rods in a tension zone. There is no secondary protection of structures against corrosion.

Table 1 shows the results of a field survey of industrial facilities of one of the mining and metallurgical plants.

At the same time, it was found that with a service life of up to 10-12 years in conditions of relative air humidity up to 85% and a chlorine concentration of 1-2.5 mg/m³, the condition of reinforced concrete structures is satisfactory. Wet spots and efflorescence were observed on the surface of the structures. Corrosion of reinforcing bars did not exceed 0.6 mm. The depth of penetration of chloride ions is 18-32 mm. When structures are used for a longer time, their condition worsens.

**Table 1. Field survey results**

<table>
<thead>
<tr>
<th>Object of examination</th>
<th>Life time, years</th>
<th>Operating environment parameters</th>
<th>Depth, mm</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Humidity, %</td>
<td>Chlorine concentration, mg/m³</td>
<td>Penetration of chloride ions</td>
</tr>
<tr>
<td>Solution preparation department</td>
<td>10–12</td>
<td>70–85</td>
<td>1–2.5</td>
<td>18–32</td>
</tr>
<tr>
<td>Electrolysis redistribution</td>
<td>12–17</td>
<td>60–87</td>
<td>2.5–15</td>
<td>22–42</td>
</tr>
<tr>
<td>Chlorine drying process</td>
<td>20–30</td>
<td>60–80</td>
<td>2.5–15</td>
<td>27–60</td>
</tr>
<tr>
<td>Redistribution of synthesis</td>
<td>20–40</td>
<td>75–85</td>
<td>2.0–15</td>
<td>40–68</td>
</tr>
<tr>
<td>Chlorine department</td>
<td>30–40</td>
<td>60–87</td>
<td>2.5–10</td>
<td>40–78</td>
</tr>
<tr>
<td>Hydrometallurgical department of cobalt electrolysis</td>
<td>42–46</td>
<td>62–80</td>
<td>2.5–20</td>
<td>40–90</td>
</tr>
<tr>
<td>Hydrometallurgical Department of nickel Electrolysis</td>
<td>40–45</td>
<td>60–90</td>
<td>2–20</td>
<td>42–85</td>
</tr>
</tbody>
</table>

So, after 20-30 years, under conditions of relative humidity of 60-80% and chlorine concentration of 2.5-15 mg/m³, the structures had significant corrosion damage. In addition to wet spots, efflorescence, rusty imprints of reinforcement, cracks were observed along the reinforcing bars, spalling of the protective layer of concrete.

The penetration depth of chlorine ions was 27-60 mm, the reinforcement corrosion was 3.8-6.2 mm. The condition of the structures ranges from unsatisfactory to emergency. Longer operation leads the structure to an emergency state.
3 Results

On Figure 1 presents the experimental data and analytical dependences of the advancement of the front of chloride concentrations dangerous for reinforcement and the destruction of concrete under the action of the medium under consideration.

![Graph showing the advancement of chlorine ions deep into the concrete in time](image)

**Fig. 1.** Promotion of chlorine ions deep into the concrete in time

The most complete experimental data on the movement of chlorides describes the dependence

\[ h_{cl} = 4.5 \tau^{0.7}, \]

where \( h_{cl} \) is the penetration depth of chloride ions; \( \tau \) - time of operation of structures; 4.5; 0.7 - empirical coefficients depending on the properties of concrete and the environment; the correlation coefficient is 0.92; coefficient of variation 18%.

Transforming dependence (1), we determine the estimated service life of reinforced concrete structures \( \tau_p \) by the factor of the passing action of the concrete protective layer

\[ \tau_p = \exp\left(1.42 \ln \frac{a_b}{4.5}\right), \]

where \( a_b \) is the thickness of the protective layer of concrete.

Formula (2) is recommended to be used when determining the service life of reinforced concrete structures made of concrete of normal density of classes B12.5-B20 on medium aluminate Portland cement.

When carrying out major repairs and reconstruction of industrial buildings and structures, when the protective properties of concrete are completely exhausted and reinforcement corrosion is observed, it is advisable to determine the service life of reinforced concrete beams and slabs based on the reserve of their bearing capacity for planning repair and restoration work.
For this purpose, the coefficient \( k_t \) is used, which represents the ratio of the actual bending moment from external loads to the actual bearing capacity of the element section.

The performed studies made it possible to establish a statistical relationship between the time of formation of corrosion cracks in the protective layer of concrete, arising under the action of reinforcement corrosion products, and the thickness of the protective layer.

\[
\tau_b = 0.055a_b^{1.7},
\]

where \( \tau_b \) is the moment of formation of corrosion cracks in the protective layer of concrete; 0.055; 1.7 - empirical coefficients; confidence level 0.95.

On Figure 2 shows the experimental data on the corrosion failure of the working reinforcement of reinforced concrete beams and slabs of monolithic floor.

![Fig. 2. Development of reinforcement corrosion over time](image)

\( a_b \) values depend on the parameters of the gas-air medium and the properties of reinforcing steel: \( a_b = 20 \); \( a_b = 30 \); \( a_b = 45 \) mm

The empirical dependence of the service life of the structure \( \tau \) on the depth of corrosion (diameter reduction) of the reinforcement is determined by the formula

\[
\tau = \frac{\delta}{\Delta + \tau_b - (\tau_b - \tau_p) \times \exp \left[ \frac{\delta}{\Delta(\tau_b - \tau_p)} \right]},
\]

where \( \Delta \) is a value depending on the parameters of the gas-air medium and the properties of reinforcing steel: \( \Delta = 0.25 \); the correlation coefficient is 0.89; coefficient of variation 15%.

We introduce the coefficient of corrosion wear of reinforcement \( k_s \), which is the ratio of the cross-sectional area of corroded reinforcement to the cross-sectional area of reinforcement before corrosion, and express \( \delta \) through \( k_s \).
For single row arrangement of reinforcing bars

\[
\delta = 0,25 (1 - k_s) d \sqrt{n},
\]

where \( n \) is the number of working reinforcement bars.

4 Discussion

In case of corrosion failure of the tensile zone of reinforced concrete bending elements, when determining \( k_s \), according to the reserve coefficient \( k_r \), for various types of section of elements, the number and diameters of rods, it is recommended to use the following formulas.

1). For rectangular section with single reinforcement:

\[
k_s = \gamma_1 - \sqrt{\gamma_1^2 - k_r (2 \gamma_1 - 1)},
\]

where

\[
\gamma_1 = \frac{R_b b h_0}{R_y A_s},
\]

\( b \) - element section width;
\( h_0 \) - working height of the section;
\( R_y \) - is the design tensile strength of the reinforcement.

2). For a rectangular section with double reinforcement:

\[
k_s = k_r = -\gamma_2 + \sqrt{\gamma_2^2 + k_r (2 \gamma_2 - \gamma_3 + 1)} + \gamma_3,
\]

where

\[
\gamma_2 = \frac{R_b b h_0 + R_{sc} A_s'}{R_y A_s},
\]

\[
\gamma_3 = \frac{R_{sc}^2 A_s'^2}{R_y^2 A_s^2},
\]

\( A_s, A_s' \) - cross-sectional area of tensioned and compressed reinforcement;

\( R_{sc} \) - design resistance of reinforcement to compression.

3). For T-section with single reinforcement:

\[
k_s = \frac{\gamma_4}{2} - \sqrt{\frac{\gamma_4^2}{4} + k_r (\gamma_4 - 1)},
\]

where
The life time of structures in the case under consideration is determined by formula (4) at \( \gamma \), found through \( k_t \) and \( k_s \). At the same time, it is not allowed to violate the compatibility of the operation of the reinforcement with concrete, for which the time \( T_b \) should not exceed \( \tau_b \).

5 Conclusions

When carrying out scheduled preventive repairs of buildings and structures of non-ferrous metallurgy enterprises with a highly aggressive gas-air environment containing chlorine, the service life time of reinforced concrete monolithic floors made of concrete of classes B12.5-B20, grades W2-W4 on medium aluminate Portland cement is recommended to be determined by the formula (4), based on the reserve of their bearing capacity.

References


