Simulation of Corrosion Fracture of Nano-Concrete at the Interface with Reinforcement Taking into Account Temperature Change

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Abstract

The paper describes the proposed model for predicting the temperature dependence of the corrosion rate of steel in contact with concrete. The predicted values of the corrosion current density depending on the monthly temperature change are described. The main relations of the new mathematical model are formulated, taking into account a set of extended criteria for analyzing the influence of temperature changes on corrosion processes. For this case, changes in the value of the corrosion current density over the years are presented. In this way, the most optimal criteria and the procedure for developing these criteria using information technologies for assessing the resource of nano-concrete with reinforcement have been considered.

Keywords 1

steel, metal of pipeline, strength criterion, surface defect, crack, mathematical model, corrosion rate, effect of temperature, corrosion current, nano-concrete, interface, reinforcement, Kaeshe type relation

1. Introduction

Reinforcements for concrete constructions of the sewage network are made of steel. The efficiency of the system of transportation, cleaning and disposal of dirty sewage depends on the thermal regimes of sewer pipes, which creates conditions of potential environmental risk and emergency danger for the local population.

During the construction of networks, underground reinforced concrete pipes with a diameter of 1200 mm are used, which are made of high-strength concrete [1].

Corrosion processes take place on the interface between reinforcement and concrete in underground sewer pipes, which are facilitated by soil moisture. The result of corrosion is the formation of microcracks and cracks. The growth of the cracks eventually ends with the corrosive destruction of concrete.

In this context, it is expedient to analyze the dynamics of corrosion processes and develop recommendations regarding the forecast regarding the influence of thermal regimes on the conditions of destruction of concrete elements of structures. Forecasting of thermal regimes should be performed,

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since changes in the effect of humidity on the metal of the pipe fittings during periodic (climatic) changes in the ambient temperature (winter ... summer) stimulate corrosion processes.

Solving the tasks of ensuring technical and environmental safety for sewerage network facilities is an actual direction of research, since the existing sewerage system of large cities of Ukraine is "worn out" by 70%, and in most small cities with a population of up to 30–50 thousand people, it is completely absent , or is not used [1]. The relevance is connected with the prospect of controlling corrosion processes on the interphase surface of the metal of the armature, taking into account the relevant effects of temperature and humidity on these processes. In this context, it is worth diagnosing the modes of influence of changes in temperature and humidity and developing measures aimed at assessing the resource of sewer pipes in operating conditions.

2. Related works

Temperature effects on the metal surface in aggressive environments have been analyzed in many scientific works, in particular in [2, 3]. In scientific articles [4, 5], elements of modeling thermal effects in underground structures that are in contact with the soil electrolyte are proposed.

Important in this context is the study of corrosion formations in surface and interfacial metal defects such as pores and cracks [5, 6]. The change in metal temperature and the effect on corrosion processes in underground elements of structures can be manifested seasonally [6, 7]. Such changes are accompanied by the influence of heat on the migration processes of moisture in concrete.

It is also known that oxygen diffusion through the soil layer around the perimeter of the pipe will be variable under the influence of temperature [7]. It also affects the rate of corrosion formations. In the complex, consideration of the following effects such as seasonal influence on concrete of variable temperature, oxygen diffusion in soil and concrete, as well as the rate of corrosion formations at the interface between steel reinforcement and concrete are not considered in scientific publications. Moisture and oxygen pass through the concrete and reach the surface of the metal. There, corrosion products are formed on the interfacial surface. Corrosion products initiate the formation of corrosion defects. And corrosion defects, i.e. cracks, lead to corrosion destruction of concrete.

Corrosion of reinforcement causes horizontal cracks that violate the integrity of the protective layer of concrete [8]. Randomly located cracks arise from concrete shrinkage [8]. Exfoliation of the surface layer of concrete occurs due to the effects of an aggressive environment, alternating freezing and thawing, moistening and drying [8].

The description of this type of triple effect is an important scientific problem. The study of these effects will allow to model the corrosion (anode) current and predict the development of cracks, as well as to estimate the resource of underground reinforced concrete structures.

The methods [9, 10] describe the prediction of currents and voltages in the defect on the interphase surface between concrete and steel reinforcement taking into account artificial neural networks (ANNs) [11, 12]. These data are useful for modeling the same processes and for other similar materials. However, studies were conducted for gas and oil pipelines. Criteria and parameters are considered in works [13–19]. The topics of corrosion detection and resource assessment are investment-attractive projects [20, 21]. Because repair or replacement requires large capital investments.

The purpose of the study is to model the anodic current in a crack-like defect on the interphase surface of the reinforcement and to study its influence on the corrosion destruction of nano-concrete taking into account temperature changes, the influence of mechanical loads, humidity and diffusing oxygen.

Achieving the formulated goal involves the performance of such tasks:

- prepare information on corrosion currents for thermal regimes in surface defects at the interface with reinforcement.
- to form criterion relations of a new mathematical model for analyzing the influence of temperature changes on corrosion processes and conditions of concrete destruction.
- to form criterion relations and optimization procedure of a new mathematical model for analyzing the influence of mechanical loads and thermal conditions on corrosion processes and the conditions of the destruction of nano-concrete in the nanoconcrete- reinforcement system.

3. Proposed methodology/model/technique

According to methods [9, 10], taking into account artificial neural networks (ANNs) [11, 12], it is proposed to forecast currents and voltages in the defect on the interface between concrete and steel reinforcement. Experimental data for this type of assessment were obtained as a result of diagnosing a section of an underground metal structure with NCCM (non-contact current meter) and PPM (polarization potential meter) devices [10–13]. It is also proposed to use the method of predicting the metal resource of an underground structure with a surface crack-like defect, taking into account the hydrogen index of the soil electrolyte at the interface with the metal [3, 10–13].

From Figure 1, there is presented the reinforcement covered with corrosion and the destruction that occurs when corrosion spreads into the concrete. In the first stage, small cracks begin to appear from the metal, then the cracks widen and chipped parts are formed. Such cracking leads to the destruction of the structure itself in the future.

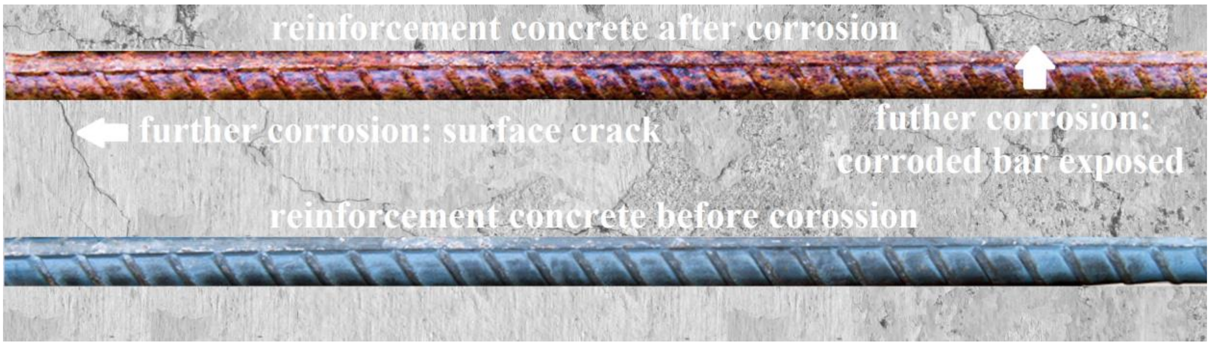

Figure 1: Example of influence reinforcement concrete after corrosion

Concrete is a porous material, as well as reinforced concrete. Reinforced concrete sewer pipes are underground and in contact with the soil. The soil is characterized by a certain moisture content at different times of the year. Moisture, together with oxygen, penetrates through porous concrete and condenses at the concrete-reinforcement interface [14]. The rate of moisture passage through concrete to reinforcement can be described by diffusion equations (for example, as in [14]).

Corrosion products of steel and hydrogen accumulate in the pores at the concrete- reinforcement interface [15].

To estimate the electric current density in the pore, which turns into a crack, there is used a generalized equation of the Kaeshe type [6, 16]:

$$I_a = I_0 \cdot \left(\exp\left(\frac{DE}{a}\right)\right) \cdot (1 + \beta_W \cdot W_{PL});\ I_0 = \frac{\alpha \cdot \chi \cdot \Delta\Psi_{ak}}{\delta \cdot \ln\left(\frac{h + c + r_c}{\delta}\right)}, \quad (1)$$

where a is the Tafel parameter of the anode metal dissolution process; $DE = E_0 - E_a$;

I_0, E_0 – corrosion current density and corrosion potential of metal;

I_a, E_a – is the anode current density and the anode potential for metal.

δ – crack opening; α is the angle at the crack tip; χ is the electrical conductivity of the electrolyte; $\Delta\Psi_{ak}$ – is the ohmic change of potential between the anode and cathode parts (anode - top, cathode - crack sides); $h+c+r$ – total depth of defect (pores and cracks); W_{PL} is the energy of plastic deformation per unit of surface.

The results of experimental studies (Fig. 2) can be used to estimate the concentration of hydrogen in the pores at the concrete- reinforcement interface [15].

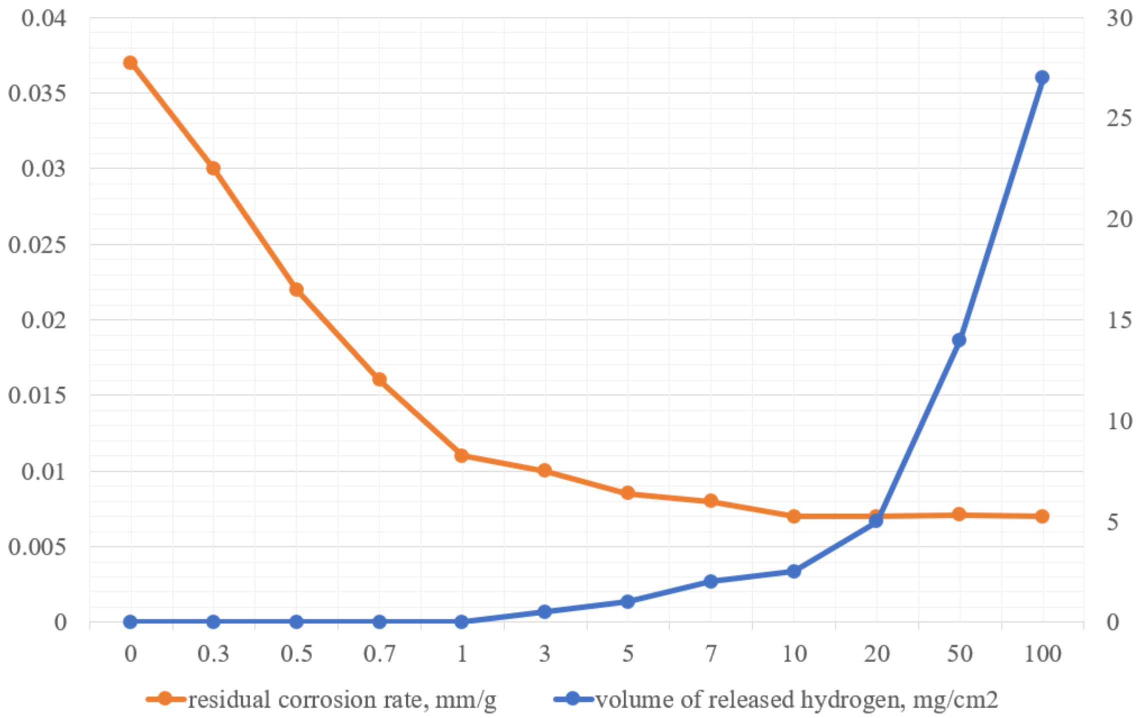

Figure 2: Dependence of the residual rate of corrosion and the volume of released hydrogen on the degree of excess of the cathodic protection current over the limiting oxygen current

Figure 2 shows the residual corrosion rate density I_{a*} mm/year a long the Y axis on the left, and the volume of released hydrogen V_H mL/cm^2 on the right Y axis.

As criteria for the destruction of concrete (in particular, nano-concrete), there is taken into account the Griffiths–Irwin–Orovan criterion and the Irwin condition for KIN K_I [16, 17]:

$$\sigma_* = \sqrt{\frac{2E \cdot WPL}{\pi \cdot L_T(1-\nu^2)}}, \qquad K_{1C} = \sqrt{\frac{2E \cdot WPL}{1-\nu^2}}, \qquad K_1 = K_{1C}, \tag{2}$$

The first two formulas are written for plane strain; E, ν – Young's modulus and Poisson's ratio, respectively; σ_* – critical stress (in particular, corresponding to the limit of strength $\sigma_в$), Pa; WPL – surface energy of plastic deformation of nanoconcrete, J/m^2; K_{1C} – fracture toughness of nanoconcrete material, $Pa/m^{1/2}$; L_T – defect length (pores), m; $WPL = J/2$; J – the Rice integral for nanoconcrete.

Limit value $\delta_1=\delta_{1C}$ is included in the criterion of strength (critical crack opening), which determines the ultimate equilibrium state of an elastoplastic body (pipe) at the moment when the crack reaches the opening δ_{1C}, to which a certain value corresponds K_{1C} and surface energy of plastic deformation WPL concrete [16, 17]:

$$\delta_1(L_T \cdot \sigma_T) = \delta_{1C}, \qquad \delta_1 = 2 \cdot \frac{WPL}{\sigma_T}. \tag{3}$$

Since $\sigma_в > \sigma_T$ under the condition of the given operating internal pressure p, the crack will propagate until the Irwin condition is fulfilled $K_1=K_{1C}$ (destruction criterion) (2).

Between the concrete (nanoconcrete) and the metal of the reinforcement, it should be sufficient adhesion. The interphase layer between metal and nanoconcrete is characterized by 4 main energy parameters: the energy of adhesive bonds γ_{ad} and its change $\Delta\gamma_{ad}$; change in interfacial tension $\Delta\sigma_m$; change of interfacial energy $\Delta\gamma_m$; change in adhesion performance ΔA_{ad} [18].

There are formulated restrictions on the listed parameters, which are similar to those in the article [18]:

$$\Delta\sigma_m \le \Delta\sigma_{m*}, \Delta\gamma_m \le \Delta\gamma_{m*}, \Delta A_{ad} \le \Delta A_{ad*}, \Delta\gamma_{vad} \le \Delta\gamma_{ad*}, \Delta W_{PL} \le \Delta W_{PL*}. \tag{4}$$

where $\Delta\sigma_{m*}$, $\Delta\gamma_{m*}$, ΔA_{ad*}, $\Delta\gamma_{ad*}$, ΔW_{PL*} – empirical constants. Restrictions on the energy parameter W_{PL} written similarly to the previous 4 parameters.

Ratios (2)–(4) constitute a complex criterion of strength for nanoconcrete, which is in contact with the corrosion pore formed at the interface between the metal of the reinforcement and concrete. The parameters of expressions (2)–(4) are determined on the basis of the experiment, and the parameters of the ratio (1) will be determined on the basis of the computational experiment.

Term of trouble-free operation of a reinforced concrete sewer pipe T_S (i.e. resource) can be estimated using a similar formula [17]:

$$T_S = (h_{ch} - h_C)/V_C = T_{S1} + T_{S2}, \tag{5}$$

where $h=h_C$ – geometric size of the corrosion pore; T_{S1} – the term of preliminary operation of the pipe (the initial value that is set).

Quality criteria for the nanoconcrete-steel reinforcement system. Similarly to the article [18], the multiplicative qualitative quality criterion for reinforced concrete of a sewer pipe is given in the form:

$$Z_1 = \prod_{i=1}^{m} k_i \,, = k_1 \cdot k_2 \cdot k_3 \cdot k_4 \cdot k_5 \cdot k_6 \cdot k_7 \cdot k_8 \cdot k_9 \rightarrow max, \tag{6}$$

where k_i – parameters (i=1, 2, ..., 9) that characterize the technological process improvement plan, in particular: k_1 – management and control of data related to the monitoring of the "metal-concrete" system; k_2 – susceptibility and risk techniques; k_3 – methods of estimating parameters of the state of interphase layers taking into account (1)–(5); k_4 – methods of assessing the condition of surface defects (pores, cracks) taking into account strength criteria, (2)–(5); k_5 – methods of evaluating the results of the evaluation of corrosion currents (1); k_7 – risk assessment techniques; k_8 – methods of responding to emergency situations; k_9 – performance management techniques (key performance indicators).

Here it can be also considered alternative utility functions, such as Chebyshev scalarization, Derringer Suich or Harrington Desirability functions. They have strong conceptual advantages.

There is also introduced a quality criterion Z_2 in the additive form similarly to [18] and the combined criterion Z_K taking into account a number of parameters k_j [18]:

$$Z_2 = a_1k_{10} + a_2k_{11} + a_3k_{12} + a_4k_{13} + a_5k_{14} + a_6k_{15} + a_7k_{16} + a_8k_{17} + a_9k_{18}, \qquad Z_K = a_{10}Z_1 + a_{11}Z_2, \tag{7}$$

where a_j (j=1, 2, …, 11) – weighting factors, which are determined by the expert method.

Parameters k_j characterize:

k_{10} – methods of providing intermediate and periodic reviews;

k_{11} – change management techniques and clearly defined impulses for re-evaluation;

k_{12} – methods of ordering roles and responsibilities;

k_{13} – methods of using a deep learning neural network;

k_{14} – methods of forming relations with personnel and involving them in order to improve the business system [19];

k_{15} – methods of strengthening concrete using the addition of nanoparticles;

k_{16} – methods of improving the compressive strength of nanoconcrete material;

k_{17} – methods of the influence of innovations on the improvement of the structure of nanoconcrete [20] ;

k_{18} – methods of estimating the period of trouble-free operation T_S (resource) structure (reinforced concrete pipe).

In the first approximation, there is choosen:

$$a_1 = a_2 = \cdots = a_9 = \ 1/9\,; a_{10} = a_{11} = 0{,}5. \tag{8}$$

Coefficient k_{13} takes into account the procedure of using a deep learning neural network. It corresponds to a probabilistic generative model in which functions from several layers of hidden nodes are embedded [18]. A neural network is used to process the results of the examination of sections of a reinforced concrete pipe. With the help of a neural network, a model is developed that provides a forecast of the depth and length of a corrosion defect, which can be used to calculate the conditions for the increase in the size of a corrosion pore (crack).

Ratios (1)-(8) form the basis of a new mathematical model, the results of which help to predict the strength of reinforced concrete with nanoparticles from the point of view of the probability of failure and evaluation of nanoconcrete shrinkage and resource.

To optimize the compressive strength of nano-concrete and the adhesion between nano-concrete and reinforcement, there is used, similarly to the paper [19], the quality functional taking into account the inverse relationship:

$$J(P_k(X_i), FB(X_i) = \int_{t_0}^{t_k} f(\bar{y}, \bar{u}, \bar{s})dt => opt, \quad (9)$$

where $\bar{y}$ – vector of given influences ($y_j(t)$ – components of the vector, j = 1,2,…,n); t – time; $\bar{u}$– control vector; $\bar{s}$– vector of uncertain disturbances; [t_0, t_k] – time interval in which the process is considered (formation of optimal values of model parameters and energy characteristics of interphase layers between concrete and reinforcement, k=1,2,…,m); m – the total number of information and parameters related to the technology of manufacturing sewage pipes; $f(\bar{y}, \bar{u}, \bar{s})$ – a function that displays a quality indicator; $FB(X_i)$ – a function that characterizes feedback (*Feed-back*) between parameters P_i and input data taking into account risks and expert opinions. Here the symbol *opt* corresponds to the optimality condition of the functional (9).

4. Results

An example of modeling the anodic current in defects on the metal surface in sewage networks is considered. Constant humidity and temperature changes lead to the occurrence of corrosion processes, which causes the destruction of the structure over time. The number and size of defects may increase under the influence of these external factors. Particular attention should be paid to places near stations or pipelines that are in a hot state.

Since Ukraine is in a temperate climate, there is an average temperature change of 269 K in the winter period, and 294 K in the summer period. These temperature changes cause defects to increase due to the change of state.

With the help of NCCM and PPM devices [8, 22, 23], it is possible to measure anodic currents on the metal surface in defects.

The results of measuring corrosion currents in works [14, 16] and average monthly air temperatures in Ukraine from publicly available sources were used to model such a corrosion process.

Table 1 presents the values of the average air temperature for each month and the interpolated values of the anode current at 1 and 3 years of operation.

Table 1

The result of calculating the anode current density indicators according to the average temperature in Ukraine every month.

Average temperature, K	Month	Anode current density I_a (1 year), A/м^2	Anode current density I_a (3 year), A/м^2
268.65	January	51.34607509	34.29184
269.85	February	51.57542662	34.44502
274.25	March	52.41638225	35.00666
281.75	April	53.84982935	35.96399
287.85	May	55.01569966	36.74263
291.35	June	55.68464164	37.18939
292.85	July	55.97133106	37.38085
292.25	August	55.85665529	37.30427
287.65	September	54.9774744	36.7171
281.65	October	53.83071672	35.95123
276.15	November	52.77952218	35.24918
271.75	December	51.93856655	34.68754

The highest value is observed in July and the lowest in January, due to the highest and lowest temperatures of the year, respectively. The value of the anode current decreases by almost half in 2 years of unchanged operating conditions.

The results were visualized using Table 1. Fig. 3 shows the change in the anode current during the months for the values collected after one and three years.

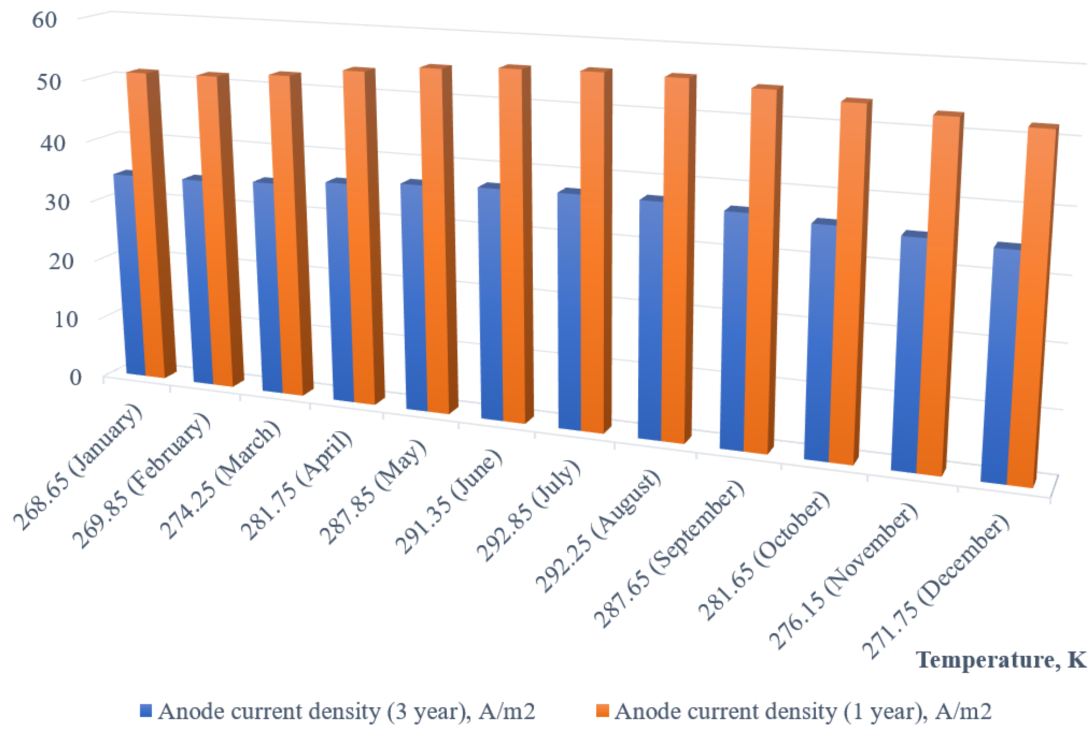

Figure 3: Changes in indicators of anode current density according to the average temperature in Ukraine every month

Figure 4 shows the difference between the anode current values, which are described in Table 1. The figure shows the change in temperature according to the average temperature by month.

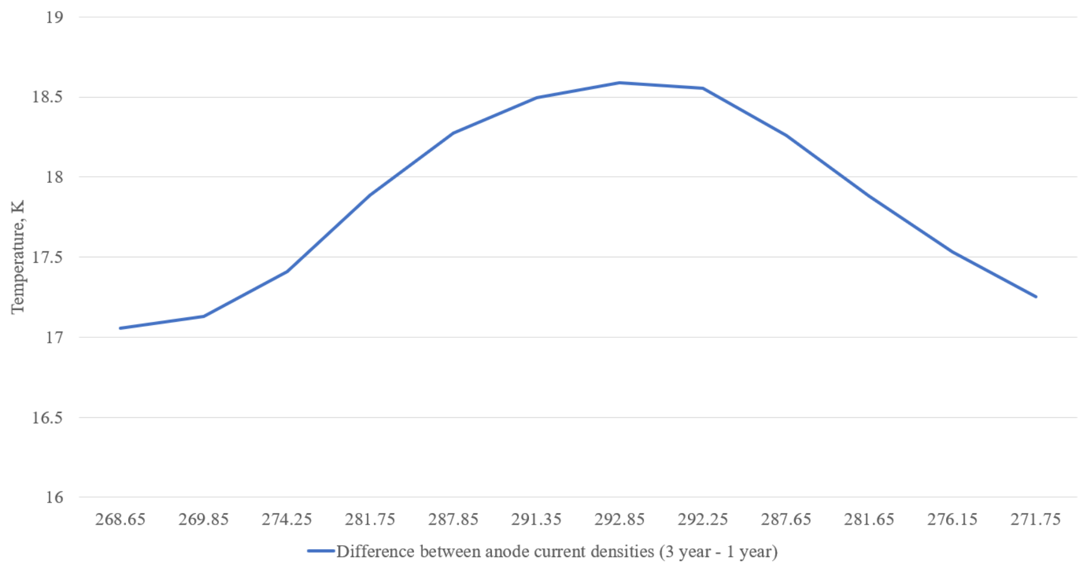

Figure 4: Difference between anode current densities for 3 year and 1 year

The biggest difference is observed in the summer months of the year and reaches 18.6 K, and the average difference is 18 K.

It can be simulated the situation of changes in anode current over time from 1 year to 9 years. Temperatures are higher, such as 331 K – 333 K can be observed near such oil pumping stations.

The values of the anode current change within 1.5 A/m^2 when the temperature changes by 20 K [14, 16].

With a fixed step for each temperature, it is possible to estimate the change in the anode current density. Therefore, at a temperature of 293 K, the fixed step of changing the value can be considered

18.6, 313 K – 20.1, and 333 K – 21.6. Figure 5 shows in a bar chart what a linear simulation of such a process might look like.

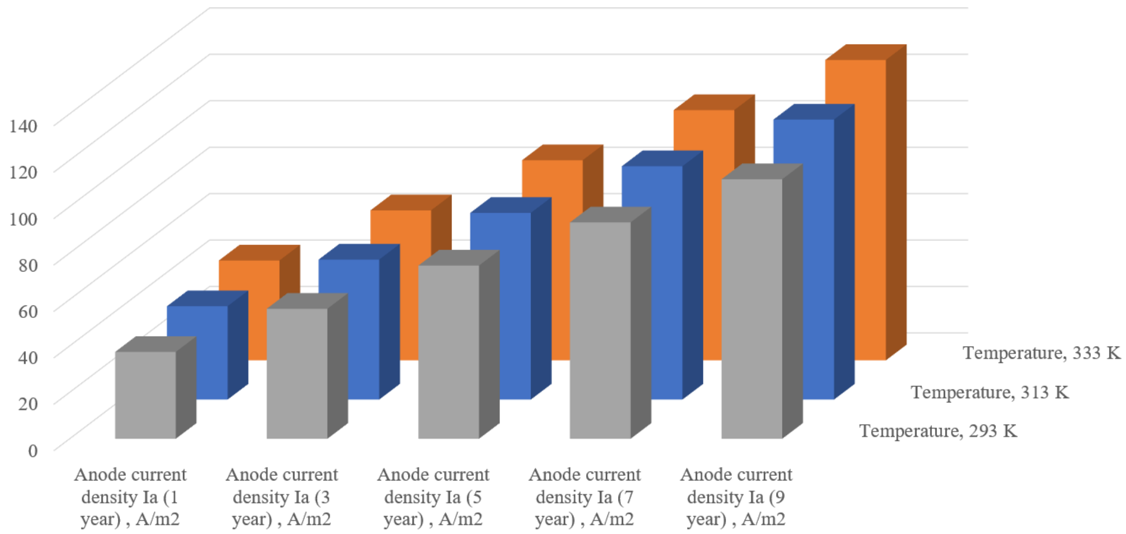

Figure 5: Estimation of change in indicators of anode current density every two years based on the fixed calculated steps 293K – 18.6 A/m^2, 313 K – 20.1 A/m^2, and 333 K – 21.6 A/m^2

In the same way, it is possible to perform simulations at other temperatures and time periods. However, the strength of the construction will decrease with the time of operation when the anode current increases, which affects the rate of corrosion propagation and destruction of the structures as a whole.

5. Discussion

The modeling of such processes depends on the climate and average monthly temperatures in a certain part of the world. The ambient temperature may differ from place to place, so for more specific calculations, it is worth taking into account the climatic features of the region.

Seasonal temperatures fluctuate within 5 degrees from one month to another. Sewage networks are constantly in a wet state, because they are in the ground. The water that falls puts a different load on the system depending on the month. Moreover, there are months in which there is a greater amount of rain, such as spring-autumn. These factors, together with others, influence the rate of corrosion propagation. From the results obtained in the paper, it can be concluded that the anodic current in such defects decreases at a lower temperature and, on the contrary, increases at an increase in temperature.

Over the years of operation and under the influence of mechanical loads and external factors, corrosion begins to spread, which affects the destruction of concrete at the interface with reinforcement. It is worth paying attention that the strength of concrete is affected by the components, the best ways to strengthen nanoconcrete are nanoparticles of SiO_2 [24] or CuO [25, 26]. Thus, it will affect the duration of operation and delay the destruction.

In addition, from the obtained results, the ratio of the value of the anode current from January to July is approximately equal to 0.92 and between each month is approximately equal to 0.98.

In the work, the mathematical model takes into account Keshe-type relations for the anodic current density, a new comprehensive strength criterion for concrete, and a quality criterion, taking into account the inverse relationship between the material parameters and the corresponding initial values.

Based on the temperature values and the corresponding values of the anode current, it is possible to estimate the resource of a certain material. For this, it is worth considering the criteria in the ratios for the new mathematical model (1)–(9).

Modeling of such processes can be improved for interrelated parameters using the approach of neural networks [10, 11] taking into account the specified criterion ratios. Thus, a new mathematical model can be formed.

Temperature changes can also be monitored with the help of thermal imaging optics using computer vision to identify the most vulnerable places in the studied area. In this case, it is best to study the internal sections of the sewage system, because detection requires a photo or video stream [27]. However, such defects often appear later on the inner surface. However, this type of defect detection can be applied to a small area [25].

Thus, modern information technologies, taking into account investment projects [28, 29], methodology of constructing a production function using quality criteria (e.g. classic production function of Cobb-Douglas) [30, 31], and monitoring material degradation processes [32], can obtain optimal criteria, which are important to consider for concrete failure analysis.

6. Conclusion

1. The anodic current density is evaluated for thermal regimes in surface defects at the interface between nanoconcrete and reinforcement. It is found that in the temperature range T = 313...333 K, the change in the anodic current density in the corrosion pore at the interface between nanoconcrete and reinforcement takes a value of approximately 3%, but this is enough to transform the pore into a corrosion crack.

2. Criterion ratios of a new mathematical model for analyzing the influence of seasonal temperature changes on corrosion processes and conditions of concrete destruction are formed. Modeling is performed on the basis of average monthly temperatures for the anode current.

3. The main relations and peculiarities of the functioning of the new mathematical model (1)–(9) for analyzing the influence of temperature changes on corrosion processes, which lead to the formation of corrosion pores at the interface between concrete and steel reinforcement, are formulated. In particular, the basis of the new model is the Keshe-type ratio for the anodic current density, a new comprehensive strength criterion for concrete, as well as an optimization approach for calculating interconnected parameters using neural networks and a quality criterion and taking into account the inverse relationship between the material parameters and corresponding initial values.

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