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Effect of concreting defects on the uptime of reinforced concrete during the construction of new Arctic settlements by the criterion of exposure to air carbon dioxide

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Abstract. The development of Arctic territories and waters requires the construction of new settlements with industrial infrastructure. Modified concrete is used for the construction of these facilities. However, during erection of monolithic reinforced concrete structures defects and damages are formed, which affect their durability and reliability. The results of probabilistic simulation of failure-free operation of reinforced concrete according to the criterion of carbon dioxide gas effect on concrete for conditions of Sabetta settlement are given in the work. Concretes with a water-cement ratio of 0.35 and 0.50 per CEM III/A 42.5N were taken as design values. Design thickness of the protective layer is 45 mm, depth of defects and damages is 5, 10, 15, 25 mm. Probability modeling was performed using the Duracret model using Excel and PTC Mathcad. The results showed that without defects and damages the period of normal operation as a whole corresponds to the design value of 50 and 100 years. In case of defects, the first local areas may appear in 15-40 years.

1. Introduction

Global climate change allowed Russia intensively developing the territories and waters of the Arctic zone. Over the past 10-25 years, new and existing settlements (New Port, Sabetta, Harasavay and others) have formed and expanded. Functional assignments of these settlements are transport and logistics points of the Northern Sea Route, watch settlements of oil and gas, tourism industries and other activities. Thus, in Yamalo-Nenets Autonomous District, Novatek built Sabetta settlement for 30,000 workers. The key tasks of this settlement are the production of liquefied natural gas (hereinafter LNG) and its transfer to special maritime vessels. The design life of the village buildings and structures is at least 50 years of operation, and in some cases at least 100 years.

In industrial infrastructure settlements, carbon dioxide (hereinafter referred to as CO2) is one of the most aggressive gaseous media generated by emissions into the atmosphere. It penetrates into concrete pores, carbonizes cement stone and contributes to exhaustion of concrete passivating properties in steel reinforcement zone, contributing to its corrosion [1]. Increased concentration of gas 0.1... 0.2% by volume is present near the flare plant, process machines and equipment or in the closed space of the industrial zone. The industrial infrastructure for Sabetta Township is the LNG plant.

In order to achieve the design term of building structures of buildings and structures, requirements for resistance to cyclic freezing and thawing, exposure to chemical and biological media must be imposed. One of the most promising construction materials in harsh climatic and operational conditions is reinforced concrete with the use of modified concrete with high operational indicators. The example of the use of such concrete is the construction of the Kisloguba Tidal Power Plant. According to [2], no damage was detected in the concrete during the examination of its structures after 42 years. The main structures of reinforced concrete in Sabetta Township are LNG tanks, foundations for process plants, special port structures and other facilities.

The imperfections of technologies and distance of construction sites from developed infrastructure contribute to the formation of defects and damages of reinforced concrete. For example, according to the conclusion «Technical Survey of Bearing Reinforced Concrete Structures of LNG Plant Construction Facilities in the Territory of Yuzhno-Tambey Gas Condensate Field», prepared in 2016 by the employees of the «Design and Technological Bureau of Concrete and Reinforced Concrete», which assessed the technical condition of the monolithic walls of LNG tanks after construction. It follows from the conclusion that after completion of construction there are cold concreting seams in LNG tanks, shrinkage cracks with opening width more than 0.2 mm, caverns, chips, etc. In addition, zones of concrete inhomogeneity in locations of the thickened frame were detected by ultrasonic flaw detection.

The most characteristic defects and damages include low strength of concrete, presence of shells, chips, cold seams, through and surface cracks, internal tightness of concrete structure, etc. They are formed due to violation of the technology of formwork, reinforcement and concrete works, as well as the use of raw materials with low properties, unsatisfactory concrete care during hardening and other factors. Another factor that reduces the quality of construction is the long delivery time of materials. Thus, the supply of binding substances is at or above the guaranteed date. This is because shipping is typically done by maritime transport.

The defects and damages affect the failure-free operation of the structure and structure as a whole. Surface damages (chips, sinks and cracks) are generally repaired with special compositions based on high-grade cements. Internal damages in the form of leaks of concrete of different size, as a rule, are non-repairable and require the arrangement of secondary protection measures (finishing with coating or adhesive insulating materials) or carrying out measures to demolish all or part of the structure. However, in practice there are cases of neglect of these damages if their volume does not affect the bearing capacity of the structure.

The defects and damages can significantly reduce the life cycle of reinforced concrete. In order to assess its stability, it is necessary to carry out appropriate studies in the field of evaluation of primary protection measures according to the criterion of impact of CO2 affecting the period of failure-free operation taking into account defects and damages received during construction.

2. Materials and methods

As the subject of the study, we will accept the monolithic wall of the LNG tank without defects and with defects and damages in the design section. The subject of the study is the period of failure-free operation of the protective layer of reinforced concrete as an effective measure of primary protection. Concrete is made on CEM III/A 42.5N binder, with additives: superplasticizer "SIKA VISCOCREE S-600 SP"; Air intake additive "SIKA AER 2005"; "SIKA RETARDER 12" concrete mix setting retarder. Water-cement ratio of 0.35 and 0.5 is used to simulate concrete porosity. The design thickness of the protective layer is 45 mm and corresponds to the outer face of the LNG tank wall.

Failure-free operation can be represented as a set of parameters: probability of risk of neutralization of protective layer p_f, probability of failure-free operation $P(T)$; reliability index β.

The definition of parameters p_f was realized by the inequality of the species, according to the works [3, 4]:

$$p_f\{a_{ap} - x_{carb}(T) < 0\} \leq p_0\,, \tag{1}$$

where p_f – probability of risk of neutralization of protective layer,%;
a_{ap} – actual (predicted) thickness of protective layer of reinforced concrete, mm;
$x_{carb}(T)$ – concrete carbonation depth, mm;

p_0 – design probability value,%.

In order to calculate the reliability parameter of the design [3], the reliability index β is proposed, which is a multiplier and characterizes the information on the coefficient, at the same time the standard deviation of the variable Z is quantifiably different from the distance between the zero point and the average value Z, i.e.:

$$p_f = f\left(-\frac{\sigma_Z}{\mu_Z}\right) = f(-\beta), \quad (2)$$

where f – a function of the standard normal distribution;

μ_Z – the median of the variable Z;

σ_Z – the standard deviation of the variable Z.

The probability of failure-free operation of the structure by the criterion of carbonization of the protective layer is determined by the following dependence proposed in the works [5, 6]:

$$P(T) = P\left\{\frac{N - n(T)}{N} \times 100\%\right\}, \quad (3)$$

where N – number of scenarios of concrete carbonation rate;

n_0 – number of failures or failure of mode condition (1) in a certain period.

Actual or predicted thickness of the protective layer taking into account its deviations can be represented as:

$$a_{ap} = a_p \pm \{a_{min}; \Delta a_{max}\}, \quad (4)$$

where a_p – design thickness of protective layer, mm;

$a_{\min}$ – lower limit of thickness deviation, mm;

$\Delta a_{\max}$ – upper limit of deviation, mm.

The lower limit depends on the maximum allowable thickness of the protective layer, as well as the presence of defects and damages reducing the thickness due to the possibility of penetration of the aggressive medium. The $a_{\min}$ parameter is proposed to be defined as follows:

$$a_{\min} = \Delta a_{\min} + \sum_{i=1}^{i} a_1 + a_2 + ... + a_i, \quad (5)$$

where $\Delta a_{\min}$ – maximum permissible value of the thickness deviation of the protective layer, mm;

a_1, a_2, a_i – depth values of various types of defects and damages in the design section, mm.

$\Delta a_{\min}$ и $\Delta a_{\max}$ in Russia are normalized by the joint venture 70.13330.2011 “The bearing and enclosing structures”. According to it, when the thickness of the protective layer is more than 20 mm, their value is taken to be -5 and +15 mm, respectively. Thickness deviations taking into account defects and damages depend on their depth in the design section. In the case of a combination of several defects, the sum of the depths of these thicknesses may be considered. The authors consider the change of depth of concrete protective layer with defects a_i of 5, 10, 15, 20 and 25 mm depth.

The depth of carbonation in a certain period is calculated by the following formula:

$$x_{carb}(T) = x_{c,0}(T) + \varepsilon_{x_c}, \quad (6)$$

where $x_{c,0}(T)$ – depth of concrete carbonization with uniform distribution of front in sample, mm;

ε_{x_c} – random deviation of carbonized layer front in the structure, mm.

The calculation $x_{c,0}(T)$ was carried out according to the model “Duracret” [3]:

$$x_{c,0}(T) = \sqrt{2 \cdot k_e \cdot k_c \cdot \left(k_t \cdot R_{ACC,0}^{-1} + \varepsilon_t\right) \cdot C_s} \cdot \sqrt{T} \cdot W(T), \quad (7)$$

where k_e – coefficient of relative humidity of operating medium;

k_c – a hardening factor characterizing the relative hardening period of the concrete under humidity conditions;

k_t – regression coefficient;

$R_{ACC,0}^{-1}$ – reverse effective carbonation resistance in concrete, (mm^2/year)/(kg/m^3);

ε_t – error due to application of accelerated carbonization method, (mm^2/year)/(kg/m^3);

$W(T)$ – function taking into account variable wetting of concrete surface by rain precipitation in operating environment.

The main parameters of the model, including the reverse effective carbonation resistance in concrete, were taken by fib 34 «Model Code for Service Life Design», depending on the water-cement ratio of the concrete. In the case of W/C = 0.35, the value $R_{ACC,0}^{-1}$ was taken conditionally. Parameters for probabilistic simulation are given in Table 1.

Table 1. Parameters for probabilistic modeling

Parameter	Units rev.	Distribution type	W/C=0.35		W/C=0.5	
			μ	σ	μ	σ
ε_{x_c}	mm	norm	0.1029	1	0.1029	1
RH_{real}	%	beta	μ = 89.61; σ = 8.29; α = 11.24; β = 1.3; A = 0.5; B = 1			
b_c	–	norm	-0.567	0.024	-0.567	0.024
k_t	–	norm	1.25	0.35	1.25	0.35
$R_{ACC,0}^{-1}$	(mm^2/yr)/(kg/m^3)	norm	1262	181	8394	794
ε_t	(mm^2/yr)/(kg/m^3)	norm	315.5	48	315.5	48
b_w	–	norm	0.446	0.163		
a_p	mm	constant	45	45	45	45
a_i	mm	constant	0; 5; 10; 15; 20; 25			
$\Delta a_{\min}$	mm	constant	-5	-5	-5	-5
$\{a_{\min};\Delta a_{\max}\}$	mm	uniform	$a_{\min}$= (-5; -10; -15; -20; -25; -30); $\Delta a_{\max}$=15			
ToW	–	constant	0.146	0.146	0.146	0.146
b_w	–	norm	0.446	0.163	0.446	0.163
pSR	–	constant	0.96	0.96	0.96	0.96
t_0	year	constant	0.08	0.08	0.08	0.08

In order to take into account the impact of humidity on concrete carbonization, statistical analysis of data of the hydrometeorological station Tambey (located near Sabetta village) for the period from 2009 to 2019 was carried out. According to the obtained data, the construction area belongs to a wet regime with boundary values of 50 and 100%, average value of 89.61% and standard deviation of 8.29%. «PTC Mathcad» defined the basic features of the beta-distribution as shown in Table 1. To model the W(T) function, it was found that in the construction area the number of days with precipitation greater than 2.5 mm averaged 64 days.

In the works [3, 7] the effect of CO2 concentration is simulated as a constant value for the whole period of operation and does not take into account changes of it due to greenhouse effect. In turn, in work [4] it is proposed to predict gas concentration according to linear law. In this case, the model leads to a significant increase in concentration, which is not confirmed by the forecast estimates given in [8]. The most realistic in our opinion is the forecast “A2” with distribution according to the degree law, taking into account the stable growth of the economy and population in the world for 100 years. In addition to the CO2 concentration of gas in the Earth ‘s atmosphere, gas emissions in the industrial zone should be taken into account. For our calculations the gas concentration was equal to 0.00114 kg/m3.

In order to take these features into account, one may propose to describe the concentration CO2 by the following formula:

$$C_s = C_{s,atm} + C_{s,emi} = 0,0006 \cdot e^{0,088 \cdot T} + 0,0114 , \tag{8}$$

where $C_{s,atm}$ – mean CO2 concentration in the Earth ‘s atmosphere, kg/m3;

$C_{s,emi}$ – additional CO2 concentration due to emissions, kg/m3.

During the year, the concentration of CO2 varies depending on the time of the year and the change of direction of the winds. So, for the areas of the Arctic zone, according to work [9], it was established that from 2004 for 2008 average concentration of CO2 made 398.6 ppm in the winter, and in the summer of 375.4 ppm. Based on this data for probabilistic modeling, we adopted the value is 2.9 × 10-5 kg/m3.

The simulation of probabilistic calculation was carried out in Excel program, by generation of pseudo-random numbers depending on type of distribution. The estimated number of probabilistic scenarios was accepted by 1000.

3. Results and considerations

Results of probabilistic calculation of reliability index β are given in Figure 1. Dependence of the probability of failure-free operation on time a given in Figure 2.

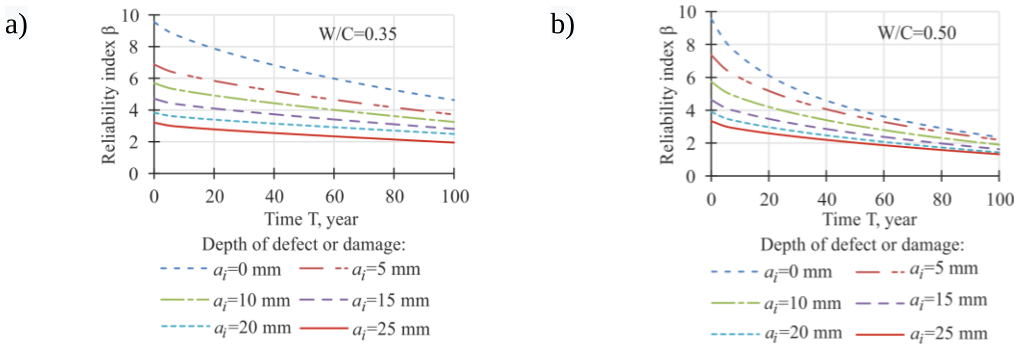

Figure 1. Reliability index versus time: a – W/C = 0.35; b – W/C = 0.5

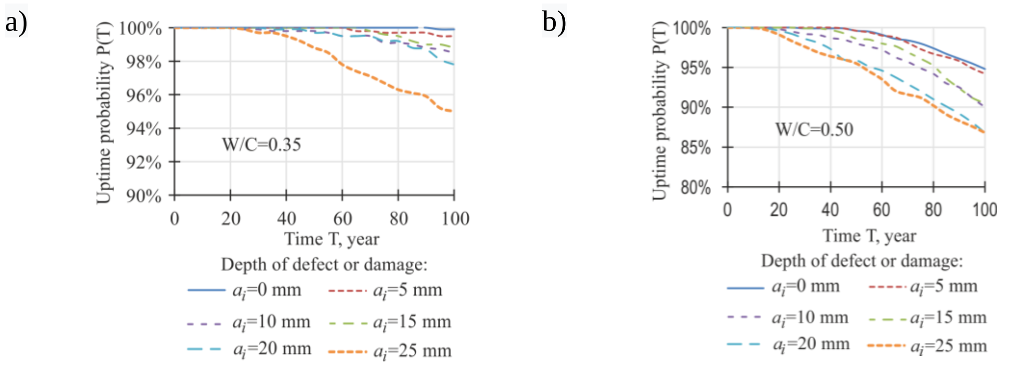

Figure 2. Dependence of the probability of failure-free operation on time: a – W/C=0.35; b – W/C=0.5

From figure 1 it is visible that structure of a protective layer of concrete in general reckon with W/C=0.35 and W/C=0.50 as reliable within 100 years of operation as β ≠ 0. However, if W/C=0.35, there is a significant discrepancy in the absence of defects from the defective results. At W/C = 0.5, the dependence of reliability index β on time showed a more intense change. For concrete with defects of 25 mm at W/C = 0.45, the reliability index was 1.9.

From Figure 2 and the classification of operation periods proposed in [6], for concrete with W/C = 0.35, the normal life of the protective layer without hidden defects will be almost 100 years. In turn, if there is a defect with a depth of 15 and 20 mm, respectively, 40 – 45 years, and for 25 mm – about 20 years. In general, the presence of defects allows characterizing the “life cycle” of the structure as a period of low (single) localization of the concrete neutralization front by the thickness of the protective layer.

The period of normal operation of the structure for concrete with W/C = 0.5 without defects and damages will be 45 years. If there are defects to a depth of 5, 10 and 15 mm, this period will be 40, 35 and 30 years. The following time is described by the period of low (single) neutralization of concrete to the whole depth of the protective layer, as the probability of failure-free operation is less than 100%. Defects with depth of 20 and 25 mm are characterized by three periods: normal operation period from 0 to 15-20 years; period of low single neutralization from 20 to 79 years; from 80 years the period of high localization of concrete neutralization front begins.

The results generally give a good forecast of the stability of the modified concrete with W/C = 0.35 under conditions of increased CO2 concentration in the Sabetta area. The inhibition of carbonation of concrete is caused by low porosity and plugging of its moisture, which comes intensively from the atmosphere and is additionally wetted by precipitation. However, the development of the village‘s infrastructure could further lead to climate change in the region. As a result, this may result in lowering the lower relative humidity threshold from 50 to 40% in the beta distribution. In this case, this will lead to an increase in the number of failures (local areas) of concrete neutralization to the depth of the thickness of the protective layer, as the number of scenarios with low humidity increases. Therefore, at the initial stages of the life cycle of reinforced concrete it is necessary to carry out appropriate studies of concrete durability under the conditions of CO2 impact according to probabilistic models.

4. Appendices

The probabilistic calculation of the period of failure-free operation of the thickness of the protective layer of reinforced concrete of the walls of LNG tanks built in Sabetta village, with a water-cement ratio of 0.35 and different depth of defects and damages, showed that the period of normal operation as a whole is 90 years without defects, with defects of different depth from 20 to 60 years. In the future it is necessary to carry out constant monitoring and control in the places of defects and to carry out evaluation of repair trains for CO_2 stability.

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