Centrum Rzeczoznawstwa Budowlanego

Open Access Journal
Modern Engineering 1 (2018) 15-25
journal homepage: https://mengineering.eu/

MODERN ENGINEERING

A probablistic model for service life prediction: reinforced concrete under the action of carbonization and chloride aggression

E.E. SHALYI * [1], S.N. LEONOVICH[2], and L.V. KIM[1]

[1]Far Eastern Federal University, Vladivostok, Russia
[2]Belarussian National Technical University, Minsk, Republic of Belarus

Abstract

A technique for reinforced concrete service life prediction under the combined effect of carbonization and chloride aggression with the use of finite-difference and probability models is developed. The period of corrosion initiation of the reinforcement and the propagation period for the conditions of Sakhalin shelf zone are taken into account. Field surveys of the port facilities of Kholmsk and Korsakov have been carried out. The carbonization front and the chloride content were estimated from the depth of the protective layer of concrete; A model is proposed that al-lows determining the average period before repair, taking into account the rate of degradation of the protective layer of concrete from the simultaneous action of two corrosion processes: carbonization and chloride aggression.

Keywords: reinforced concrete, carbonization, chloride aggression, service life prediction, probabilistic model

1 State of the Issue and Research Objectives

Existing models do not allow to take into due consideration possible changes in operating conditions, a combination of several factors of an aggressive environment. Complex modeling of various factors makes it possible to take into account the stochastic nature of the processes of carbonization and chloride aggression, changes in operating conditions of structures or require-ments imposed on them.

The purpose of the study: to develop a methodology for calculating of reinforced concrete structures durability for the climatic conditions of the coastal Far East seas zone from the com-plex effects of carbonization and chloride aggression.

Objectives of the study: analyze the results of studies on the complex effects of carboni-zation and chloride aggression on marine concrete; to improve the theoretical models of carboni-zation and chloride aggression, taking into account the crack formation and propagation a in the protective layer of concrete; to develop a probabilistic method for predicting the service life of reinforced concrete port structures, taking into account the complex effects of carbonization and chloride aggression; experimentally investigate the technical condition of the reinforced concrete elements of the port facilities in exploitation, and identify the specific features of their degrada-tion in the marine environment, including taking into account technological factors.

2 Verification of a deterministic model for calculating the combined effect of carbonization and chloride aggression

The deterministic model for calculating the combined effect of carbonization and chloride aggression on marine concrete based on the 2nd Fick Law was verified.

A model for solving the differential diffusion equation, J. Crank has been adopted, taking into account the effect of carbonization on the transport of chlorine ions in concrete. The basic equation has the Clform:

*Ccorresponding author: (E.E. SHALYI)

Received 15 February 2018
Available online 16 December 2018
ISSN 2450-5501
Published by Centrum Rzeczoznawstwa Budowlanego

$$\frac{\partial C_f}{\partial t} = \frac{D^*_{Cl}}{1 + \left(\frac{1}{w_e}\right) \cdot \left(\frac{\alpha_L(1-d\cdot a_c)}{\left(1+\beta_L\cdot\frac{C_f}{b}\right)^2}\right)} \quad \frac{\partial^2 C_f}{\partial_{x^2}} \tag{1}$$

where α_L and β_L - empirical constants; a_c - empirical constants; d - coefficient of de-crease in the connecting ability of chloride due to carbonization; C_{Cl} - the general content of chloride in concrete; C_f - content of free chloride in concrete; t - operation time; b - mass of knitting; x - depth of a protective layer.

Extent of carbonization of concrete is defined from a proportion

% $X_c - 100\%\ a_c$

% $KC - x\%\ a_c$

where X_c - extreme size of carbonization; KC - carbonate component.

$$KC = \frac{m_{CaCO_3}}{m_H}100\% \tag{2}$$

here m_{CaCO_3}, - mass of a carbonate component; m_H - the mass of a hinge plate of test, is defined experimentally.

Extreme size of carbonization is determined by a formula

$$X_c(t) = \sqrt{\frac{2\cdot D_{CO_2}}{a_C}\int_l^t f_T(t)\cdot f_w(t)\cdot C_{CO_2}(t)dt\cdot\left(\frac{t_0}{t}\right)^{0.12}} \tag{3}$$

where $f_T(t)$, $f_w(t)$, $C_{CO_2}(t)$ - funktion of influence of temperature, humidity and concentration CO_2 on diffusion coefficient; a_c - the coefficient defining quantity CO_2, necessary for transformation of all capable to be carbonated hydration products; D_{CO_2} - initial coefficient of diffusion of carbon dioxide in concrete.

For taking note CO_2 assessment of content of carbon dioxide in air taking into account service life of reinforced concrete structures is executed, according to data of Keeling a curve. As concentration of chlorides in the marine environment changes depending on weather condi-tions, the model of sea water impact on constructions is modified by input of dependence on distance between a construction and the coast [1–4].

For verification of model of joint action of carbonization and chloride aggression rein-forced concrete structures of the classes XC4 and XS3 under the terms of operation with average values of parameters of concrete mix according to EN 206:2013 and the minimum thickness of concrete protective layer on the joint venture 28.13330.2012 are taken. According to the offered technique, calculations for these tab. 1 are carried out.

For modeling the program in Mathcad (authors D. Shestovitsky and E. Karapetov) ex-ecuted on the basis of final and differential approach is used and modified (fig. 1, tab. 2). $C_{Cl}(x;t)$ - concentration of chloride ions in protective layer without carbonization; $C_{Clcarb}(x;t)$ - concentration of chloride ions in protective layer with carbonization. Critical concentration of chlorides – 0,4 % or 1.4 kg/m^3

Results have shown, that carbonization has led to release of chloride ions in pore's solu-tion, in the investigation of what, service life of structures decreases

3 Technique of probabilistic calculation of joint action of carbonization and chloride aggression

The technique of probabilistic calculation of joint impact of carbonization and chloride aggression on concrete is developed. The equation of probability of refusal is the cornerstone:

$$P_f = P(R - S \leq 0) \leq P \tag{4}$$

where P_f - rejection probability; P - admissible probability of approach of a limit state; S- loading function; R - function of resistance of a structures.

Table 1. Basic data of final and differential model

Parameter	Unit-ism.	Site of Sakhal in Island		
		Northern	Central	Southern
T_{max}	^oC	18.3	20.5	17.7
T_{min}	^oC	-7.3	-6.2	-2.4
W_{max}	%	86	81	85
W_{min}	%	74	76	71
w/b		0.4	0.4	0.4
b	kg/m^3	350	350	350
Carbonization				
$g_{e'}$	-	2.5	2.5	2.5
f_e	-	5	5	5
E	kJ/mol	40	40	40
R	kJ/K	$8.314 \cdot 10^{-3}$	$8.314 \cdot 10^{-3}$	$8.314 \cdot 10^{-3}$
C_s	kg/m^3	$3.890 \cdot 10^{-4}$	$3.890 \cdot 10^{-4}$	$3.890 \cdot 10^{-4}$
D_{C02}	sm^2/s	$3.399 \cdot 10^{-4}$	$3.399 \cdot 10^{-4}$	$3.399 \cdot 10^{-4}$
n_m	-	0.12	0.12	0.12
Chlorideaggression				
E	kJ/mol	41.8	41.8	41.8
R	kJ/K	$8.314 \cdot 10^{-3}$	$8.314 \cdot 10^{-3}$	$8.314 \cdot 10^{-3}$
α_L	-	0.1185	0.1185	0.1185
β_L	-	0.09	0.09	0.09
W_{ref}	%	65	65	65
$C_{env}(L)$	kg/m^3	6.2	6.2	6.2
m	-	0.4	0.4	0.4
t_0	days (years)	28(0.0767)	28(0.0767)	28(0.0767)
t	year	50	50	50

For chloride corrosion, in probabilistic statement, represents value of concentration of chlorides $C_{Cl}(x,t)$. C_crit - parameter of critical (threshold) concentration of chloride at the level of bedding of fittings, which excess leads to corrosion initiation. In this case probability of no-failure operation:

$$P_f = P(\{C_{crit} - C(x,t)\} \leq 0) \leq P \tag{5}$$

$C_{Cl}(x,t)$ decides on use of model, which is based on the decision of the 2nd law of diffusion of A. Fick by means of function of a mistake of C. Andrade

$$C_1(x,t) = C_0 \sum_{n-0}^{\infty} a^n \left[erfc\left(\frac{2 \cdot n \cdot e + x}{2\sqrt{D_1(t) \cdot t}}\right) - a \cdot erfc\left(\frac{(2n+2) \cdot e - x}{2\sqrt{D_1(t) \cdot t}}\right)\right] \tag{6}$$

Table 2. Results of modeling

Parameter	Unit ism.	Place of operation		
		Northern	Central	Southern
Front of carbonization (t=50 of years)	mm	30.8	29.6	29.4
Extent of carbonization	-	0.61	0.6	0.6
Concentration of chlorides on fittings depth without carbonization (at t=50 of years)	%	0.55	0.65	0.44
Too taking into account carbonization (at t=50 of years)	%	0.65	0.6	0.54
Time of initiation of chloride corrosion without carbonization	year	50	40	43
Too taking into account carbonization	year	45	35	30

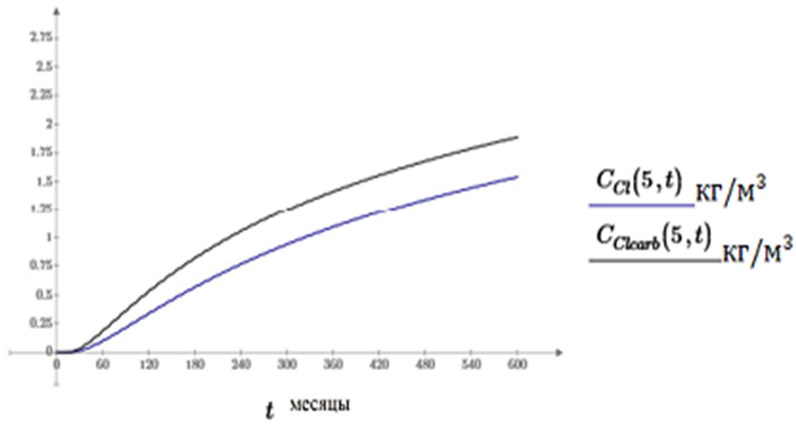

Figure 1. Change of concentration of chlorides in protective concrete layer taking into account and without carbonization (the southern site)

$$C_2(x,t) = \frac{2 \cdot k \cdot C_0}{k+1} \sum_{n-0}^{\infty} a^n erfc \left[\left(\frac{(2n+1) \cdot e + k \cdot x}{2\sqrt{D_1(t)}} \right) \right] \tag{7}$$

$$a = \frac{1-k}{1+k} \tag{8}$$

$$k = \sqrt{\frac{D_1}{D_2}} \tag{9}$$

The model is based on difference of coefficients of diffusion in one cut ("skin-effect"), that results or repair restoration of a protective layer of concrete, or at action of a set of aggres-sive factors of the external environment on a structure. In a case of joint action of carbonization and chloride aggression, formulas (6) and (7) will be transformed to a type:

$$C_{Cl_{cb}}(x,t) = Cs \sum_{n=0}^{\infty} a^n \left[erfc \left(\frac{2 \cdot n \cdot X_c + x}{2\sqrt{D_{cl,cb}(t) \cdot t}} \right) - a \cdot erfc \left(\frac{(2n+2) \cdot X_c - x}{2\sqrt{D_{cl,cb}(t) \cdot t}} \right) \right] \tag{10}$$

$$C_{Cl_{ucb}}(x,t) = \frac{2 \cdot k \cdot Cs}{k+1} \sum_{n-0}^{\infty} a^n erfc \left[\left(\frac{(2n+1) \cdot x + k \cdot (x - X_c)}{2\sqrt{D_{cl,cb} \cdot t}} \right) \right] \tag{11}$$

where C_s - superficial concentration of chlorides, %; x - thickness of a protective layer of concrete, mm; (x) - inverse function of mistakes of Gauss; $D_{cl,cb}$ - coefficient of diffusion of chlorides of carbonized concrete; $X_c = X_c(t)$ - depth of carbonization of concrete, mm; t - time, years; an and k - coefficients from formulas (8) and (9); $D_{cl,ucb}$ - coefficient of diffusion of chlorides of not carbonized concrete.

In a research resistance between layers, which results from a difference of coefficients of diffusion in one cut is also considered:

$$C_{Cl_{ucb}}(x,t) = \frac{2 \cdot k \cdot C_S \cdot R}{k+1} \sum_{n-0}^{\infty} a^n erfc \left[\left(\frac{(2n+1) \cdot x + k \cdot (x - X_c)}{2\sqrt{D_{cl,cb} \cdot t}} \right) \right] \tag{12}$$

where R - resistance between layers. $C(x,t)$calculates taking into account action of carbonization how system from formulas (10) and (12). A row of basis variables enters estimated model of combined action of carbonization and chloride aggression. Recommendations about mean values of these variables and their types of distribution are offered. For the southern part of Sakhalin Island in tab. 3 their mean values, a standard deviation and type of distribution are this.

Table 3. The concentration of chlorides for probable simulation

Parameter	Unit-ism.	Southern part of Sakhalin Island		
		Distribution type	Average value	Standard deviation
C_s	%	Const	2.5	-
x	mm	Const	vectorfr Const om a set $\{0-50\}$	-
$D^0_{ck,cb}$	m^2/s	Normal	$11.689 \cdot 10^{-12}$	$1.2 \cdot 10^{-12}$
$D^0_{cl,ucb}$	-	Normal	$2.387 \cdot 10^{-12}$	$1.2 \cdot 10^{-12}$
$D^0_{cl,ucb}$	-	Normal	$2.387 \cdot 10^{-12}$	$1.2 \cdot 10^{-12}$
k_e	-	Normal	0.67	0.05
	K	Normal	-	-
	K	Const	273	-
k_t	-	Normal	0.80	0.05
k_c	-	Normal	1	0.125
t_o	year	Const	0.0767	-
t	year	Const	vector from a set $\{t_0 - 50\}$	-
ncl	-	Beta	0.3	a=0; b=1
C_{crit}	%	Normal	0.4	0.063

For the analytical solution of a direct problem of determination of probability of resource refusal and the return problem of definition of a percentage resource of structures imitating mod-eling with calculation of necessary functionalities, for example, of the content of chlorides at the set depth, service life, etc. is used.

For computer realization in the Matlab program the calculation code for model of penetra-tion of chlorides taking into account effect of carbonization is written. Result of calculation of the program - probabilities of resource refusal of a structure and indexes of reliability during service life for various values of thickness of a concrete protective layer. At the first stage the program determines depths of carbonization and change of concentration of chlorides by depth (fig. 2-4).

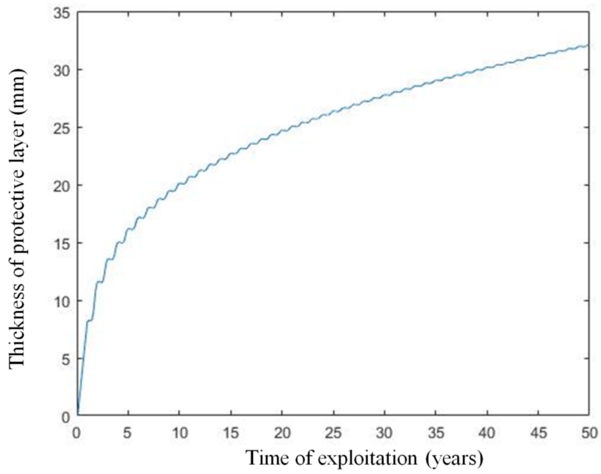

Figure 2. Growth of depth of carbonization eventually

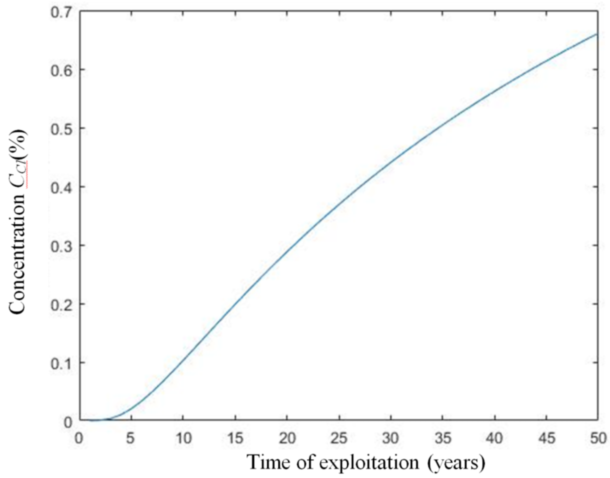

Figure 3. Change of concentration of chlorides in a zone near reinforcement for all term of an exploitation

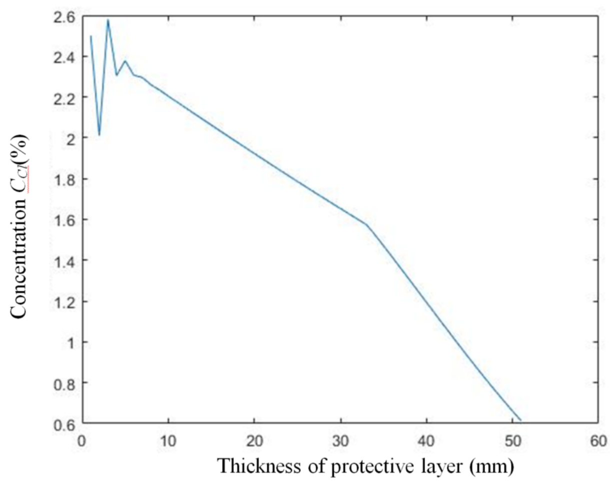

Figure 4. Profile of concentration of chlorides in zone near reinforcement in the last year of exploitation (50 years)

4 Results of natural researche

The executed natural researches: visual survey, determination of critical elements and areas, determination of strength and thickness of a concrete protective layer, the choice of test zones by results of measurements.

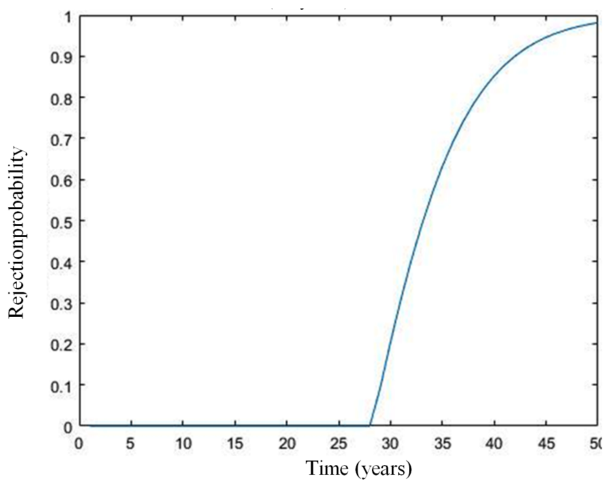

Figure 5. Probability of refusal of a construction

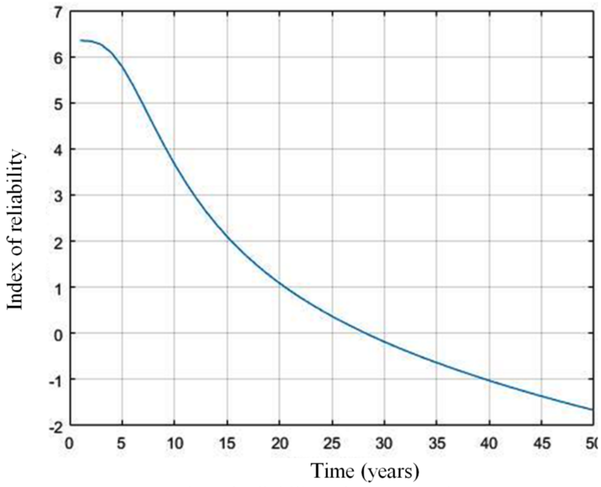

Figure 6. Index of reliability of a construction

Table 4. Probability of refusal and the index of reliability of reinforced concrete constructions, de-pending on exploitation term for the southern site of Sakhalin Island

Operationterm	Probability of refusal, p_f	indexofreliability, β
10	0.0001	3.688
20	0.005	1.102
30	0.19	-0.173
40	0.849	-1.02
50	0.981	-1.66

In test zones are carried out: visual survey for the choice of places of testing and sampling, check of concrete protective layer depth, the choice of places of sampling in "the worst places" of construction, determination of carbonization depth by phenol-phtalein test (6 and more places); selection of plates for chloride profiles (at least six plates in each test zone of the minimum size of 70x70 mm and minimum depth of 50 mm).

The laboratory is defined: by means of an ion-selective electrode value of concentration of chlorides on depth of samples, phenol-phtalein test - carbonization depth.

Results of modeling of joint action of carbonization and chloride aggression and their comparison with experimental data (tab. 5).

Table 5. Comparison of computational and experimental results

Type	The place of selection of test	Age of a coon-struction	Depth of a protective layer, mm	The measured concentration of Cl, %	The measured concentration of Cl, %	Concentration of Cl, % on probabilistic model
Holmsk sea trade port						
X4	Reinforced concrete column of the bridge	33	10	2.24	2.80	2.20
			20	1.97	2.20	1.90
			30	1.64	1.81	1.62
			40	1.10	1.20	1.03
			50	0.51	0.58	0.49
X5	Reinforced concrete beam of the bridge	33	10	2.25	2.28	2.21
			20	1.98	2.21	1.94
			30	1.68	1.82	1.62
			40	1.10	1.20	1.03
			50	0.50	0.58	0.49
Korsakov sea trade port						
K4	The base under the sign SNO	44	10	2.32	2.76	2.13
			20	1.81	2.19	1.77
			30	1.46	1.77	1.44
			40	1.10	1.17	1.07
			50	0.55	0.63	0.53
K5	Reinforced concrete foundation under pipes.	46	10	2.32	2.79	2.15
			20	1.81	1.22	1.80
			30	1.48	1.81	1.50
			40	1.10	1.23	1.10
			50	0.55	0.65	0.55

The good convergence with probabilistic model and satisfactory with final and differen-tial is received (the last doesn't consider "skin-effect"). The diffusion coefficient in final and dif-ferential model is constant at all depth of a protective layer, i.e. there is no breakdown on 2 layers with different diffusion and there is no resistance between these layers therefore concentration of chlorides in a zone near reinforcementit is overestimated. However, this model can be applicable for calculation of joint action of carbonization and chloride aggression with a small depth of carbonization when "skin-effect" doesn't exert considerable impact on concentration of chlorides in a zone near reinforcement.

Thus, with an insignificant depth of carbonization (up to 8 mm) calculation can be con-ducted on final and differential model, at considerable – values are overestimated and calculation should be conducted on probabilistic model. In practice with a depth of carbonization up to 8 mm the effect of joint action of carbonization and chloride aggression isn't considered, and the DuraCrete model is used. Thus, the most exact model - probabilistic.

5 Probabilistic model for determination of parameters for repair of a concrete protective layer

It is supposed that the irreversible consequences leading to chloride corrosion of fittings in carbonized concrete can begin already at concentration of ions of chloride of 0,2%. Using this value as critical at which it is necessary to make repairs of a concrete protective layer, and also using model for the double environment formulas (10) and (12), the program of calculation of average time and depth of repair of the damaged protective layer which also allows to predict construction service life, but already taking into account repair is developed (tab. 6 and fig. 7). As material for repair the solution similar to initial composition of concrete is chosen.

Table 6. Service life of a reinforced concrete construction, taking into account repair of a concrete protective layer

Parameter	Sur	Place of operation Southern part Sakhalin Island
Time of initiation of chloride corrosion without replacement of a carbonized layer	year	29
Design service life without replacement of a carbonized layer	year	33
Average time of replacement of a carbonized layer	year	16
Average depth of replacement of a carbonized layer	mm	24.5
Time of chloride corrosion initiation, taking into account replacement of a carbonized layer	year	45
Design service life, taking into account replacement of a carbonized layer	year	49

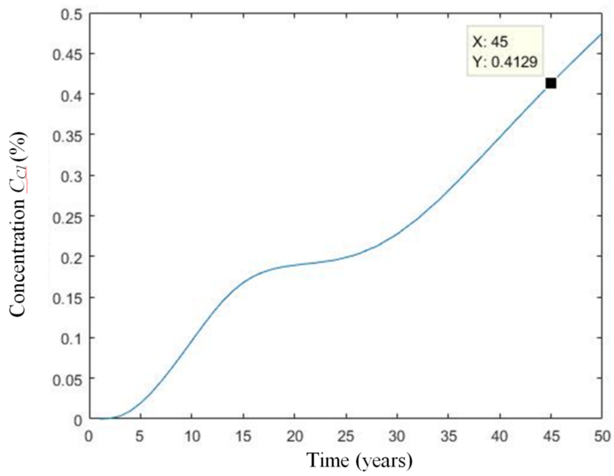

Figure 7. Change of Concentration of Chlorides in zone near reinforcement for all term of an exploitation taking into account repair

After 50 years of operation in the most adverse region of Sakhalin Island under the terms of operation, the probability of refusal was pf of =58%. Thus, repair of a construction by the me-thod of replacement of a carbonized layer new with similar characteristics increases strength. For example, in a construction, in which corrosion after 29 years of operation was initiated the mod-ern times of initiation are 45 years.

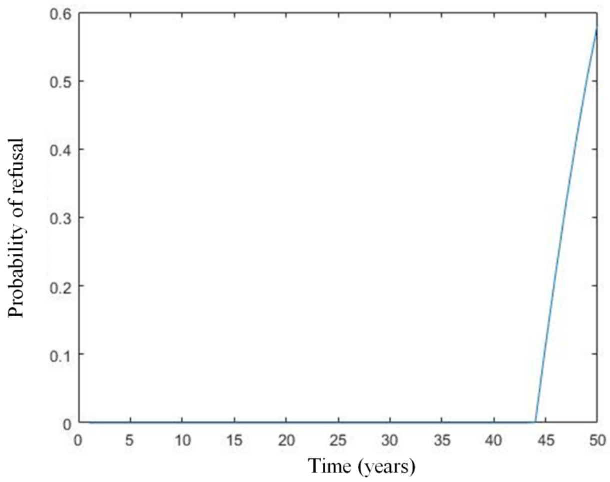

Figure 8. Probability of refusal of the repaired construction

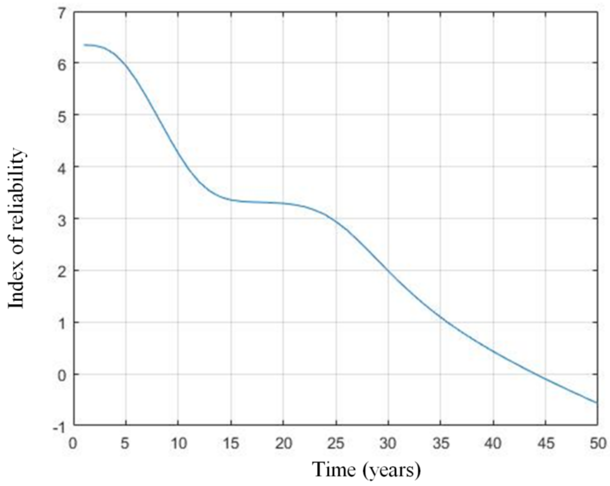

Figure 9. The index of reliability of the repaired construction

Table 7. Probability of refusal and the index of reliability of the repaired reinforced concrete con-struction, depending on operation term for the most adverse region of Sakhalin Island un-der the terms of exploitation

Operation term	Probability of refusal, p_f	Index of reliability, β
10	0.0001	4.27
20	0.0008	3.29
30	0.012	2.00
40	0.109	0.44
50	0.582	-0.57

6 CONCLUSION

1. On the basis of the analysis of models of joint action of carbonization and chloride ag-gression of a concrete protective layer and verification with experimental data the model for as-sessment of durability of sea reinforced concrete constructions considering the following factors is defined: thickness of a concrete protective layer; coefficients of diffusion of chlorides in car-bonized and not carbonized concrete; critical content and superficial content of chlorides, super-ficial amount of CO2, their time of influence; sea conditions; front of carbonization, etc.

2. The technique of determination of repair term of a constructions and depth of concrete protective layer repair of constructions is developed.

3. The technique of forecasting of durability of reinforced concrete constructions at influ-ence of the hostile marine environment, taking into account repair of a constructions is developed and with use of probabilistic model of calculation.

4. Verification of results of probability calculations of refusal of reinforced concrete ele-ments for the offered probabilistic model is executed.

Recommendations about practical use of results

The developed models allow to count the carbonization depth, concentration of ions of chloride at the set depth, the term of exploitation of a construction, time of possible repair and depth of possible restoration of a concrete protective layer for a coastal and shelf zone of the Far East.

The developed technique of forecasting of durability of reinforced concrete constructions at joint impact of carbonization and chloride agression with use of final and differential calcula-tion model is offered to be used with a depth of carbonization up to 8 mm.

The developed technique of forecasting of durability of reinforced concrete constructions at joint impact of carbonization and chloride agression with use of probabilistic model of calcu-lation can be used:

- at assessment of operational suitability (safety) at inspection of reinforced concrete constructions of coastal and shelf constructions;
- when forecasting service life of again projected reinforced concrete designs;
- when calculating necessary thickness of a concrete protective layer of the projected reinforced concrete constructions at the set service life and service conditions;
- when calculating service life of concrete in specific conditions of exploitation.
- when forecasting term of repair of the operated constructions;

The received results can be used in design of new constructions and/or repair (reconstruc-tion) of the existing constructions, operated in aggressive conditions of the marine environment and also in educational process.

References

1. Leonovich, S., Shalyi, E., Falaleeva, N. & Kim, L. *The influence of carbon dioxide on the durability of offshore concrete (English)* in. International Ocean and Polar Engineering Conference, ISOPE-2016 (Rhodes, Greece, 2016).
2. Shalyi, E., Kim, L. & Leonovich, S. *Imitating modeling of degradation of reinforced concrete designs of hydraulic engineering constructions* in. VI International symposium "Current problems of computer modeling of designs and constructions" RAASN-2016 (Vladivostok, 2016).
3. Shalyi, E., Kim, L., Leonovich, S. & Stepenova, A. *Model of calculation of depth and distribution of chlorides in concrete of hydrotechnical constructions of Sakhalin Island* in. Modern technologies and development of political education [Electronic resource]: international scientific conference (Vladivostok, 2016).
4. Shalyi, E. *et al. Level of carbonization of concrete of port constructions of Korsakovsky port.* in. Durability of construction materials, products and designs: materials of the All-Russian scientific and technical conference (Saransk, 2016).