

Kinetics of Fine Concrete Carbonation in Humid Operational Environment

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Abstract

The goal of the research was the conduction of the accelerated carbonation testing of fine concrete samples. Special attention was paid to the selection of carbon dioxide concentration, minimally affecting the results. The research on the carbonation kinetics of fine concrete samples, based on Portland concrete, exposed to the atmosphere with carbon dioxide at a concentration of 5% at a temperature of 200°C and a relative humidity of 75%, corresponding to the humid operational environment.

The following main research methods were accepted: concrete testing by etching with atmosphere with high carbon dioxide concentration, followed by the determination of the depth of concrete neutralization and the statistical processing of the results.

Keywords: durability, concrete, concrete carbonation, installation, accelerated testing, reinforced concrete, carbon dioxide, air, cement stone, concrete grade according to waterproofing qualities.

INTRODUCTION

Precast and cast reinforced concrete was, and, in the coming decades, will be the basic building material, which is confirmed by many experts. For example, according to the statistics of the Concrete Manufacturers Association in Canada [1] it was found that the annual volume of worldwide concrete and reinforced concrete application in building structures is about 5 billion m³ per year.

During the operation the main part of the erected building structures is subject to the impact of the existing liquid and gaseous corrosive environment, able to cause damage to the structures, resulting in the limited-efficiency, or even to the emergency condition of the structure. This impact is especially great in the industrial area, where the outdoor liquid and gaseous environment, contacting with the building structures, is contaminated by the products and the production wastes. The gaseous aggressive environment with the presence of carbon dioxide is most common and affects directly all building construction units contacting with air. The concentration of carbon dioxide in the air against the background of the atmosphere of the planet is not constant and has a growing character, because of the increased "greenhouse effect" caused by industrial emissions. For example, according to the data [2], the amount of worldwide industrial carbon dioxide emissions into the atmosphere is 32,578,645 mln tons, of which in China-8,715,307 mln tons, in the USA-5,490,631 mln tons, in Russia-1,788,136 mln tons. Currently, the concrete carbonation is one of the most common causes of a sharp decline in the service life of the

surface-mounted reinforced concrete structures with a lifetime of more than 20 ... 30 years. In some cases, due to the high carbon dioxide concentration in the atmosphere, the corrosion damage of the reinforced concrete structures may be observed in 2-3 years of operation. Such damage is caused by depassivation of the reinforcing steel and its corrosion due to concrete cover neutralization (carbonation) and its subsequent distortion by the steel corrosion products (rust), increasing in the volume.

In 1969 Moskvina V. [3] noted the development of the methods of calculation and design of the reinforced concrete products, operating in hostile environments, different by properties and the degree of aggressiveness, as one of the main tasks of ensuring the durability of the building structures.

The international normative and technical documents related to the protection of the durability of concrete and reinforced concrete structures (for example, EN 206-1 [4] and SNIP 2.03.11-85 [5]) lack the methods allowing to predict their durability with sufficient accuracy. This is due to the non-uniformity of the cement stone, the complexity of the physical and chemical processes of concrete carbonation (e.g., not only the hydrate phase of the cement, the "portlandite" mineral and other hydrated minerals react with carbon dioxide), the unreliability of forecasting the variability of the operational environment and the availability of technological factors, appearing in the reinforced concrete structures production.

Currently, a number of calculation models, describing the concrete corrosion process, representing the dependence of the depth of concrete neutralization on the operating time $L = f(x)$ are developed, for example, the well-known calculation models, presented in the works of Hamada M. [6], Alekseev S.N. [7], Papadakis V.G. [8], Ishida T. [9], Liang M. [10], and other researchers in this direction. These models were obtained by experimental processing the on-site investigation results, laboratory experiments and numerical methods through the instrumentality of applied mathematical programs. According to the paper [11] the developed models of the form $L = f(x)$ can be divided into two directions: the first direction is used along with the equations of mass transfer of the physico-chemical processes kinetics (most prevalent); the second direction is presented by the thermodynamic equilibrium dependence. The availability of tolerance and simplification of the mathematical apparatus, affecting the accuracy of the calculations is deemed to be the disadvantage of the first group direction. The derogation from the on-site and laboratory tests results, their cumbersomeness, the presence of many factors, the determination of which requires the development of new techniques, are deemed to be the disadvantages of the second direction.

In general, most of the models come down to a genuine solution, commonly known as "the square root of time",

which has the form of (1). The main difference between these models lies in the interpretation of A_2 coefficient. Other variants of calculation models are known. For example, when calculating using the numerical method, the authors in paper [12] obtained a model of the form (2) excluding the aggressiveness of the environment, and in paper [10] the calculation model of the form (3) was obtained. In both cases the "diffusion" and the "chemical reaction" were taken into account in calculations simultaneously.

$$L = A_2 \sqrt{t}, \quad (1)$$

$$L = A_3 \sqrt[3]{t}, \quad (2)$$

$$L = at^b, \quad (3)$$

A_2, A_3, a, b are the coefficients, depending on the concrete structure and properties of the environment.

When comparing the models of the form (1), (2) and (3), the computational error of calculations amounts to dozens of percent at long term operation.

Due to the inconsistencies in the models obtained, the study of the concrete carbonation process remains a pressing issue, requiring the experimental research.

METHODS

The duration of the on-site testing amounts to at least 9 months regardless of the type of environment, so the researchers obtain the dependence on one or two points during the inspection of the building structures and thus gather the statistical data for calculation, which are conducted according to dependence (1). However, due to the low accuracy, a large scatter of the statistical data on composition of the structures, their operational conditions and the degree of aggressiveness of the environment, the proposed calculation dependencies, obtained by the comparison of these results, include the considerable inaccuracies in determining the operational service life of the structures.

The data on the on-site testing are not numerous. For example, the data obtained by Vandalovskaya L.A. [13] for concrete samples with different water-cement ratio for several periods (more than three points), are well known. The gas air environment of the spinning mills of the viscose production is taken as the operational environment. These data are consistent with the model of the form (3), where the exponent of time is not constant and varies in the range of 2.05 ... 3.05.

The inconsistency of the data obtained during the long-term testing, and the time factor contribute to the development of accelerated methods of concrete samples testing, by increasing the concentration of carbon dioxide.

The concentration of CO_2 , able to minimize the inaccuracy of the results of the experiment, must be chosen, e.g. in paper [7], the concentration of CO_2 for the experiments was within the following parameters: 20, 10, 5, 1, 0.04%, and the time periods were respectively 10, 20, 40, 200 and 6,300 hours. In the paper [14] in the course of testing of the samples of concrete with high content of mineral additives, the concentration of carbon dioxide ($50 \pm 5\%$) was chosen, and the dependence of the form (1) was applied for the description of the data.

When selecting the CO_2 concentration it is required to consider that in case of humid mode and the CO_2 concentration corresponding to the natural background in the atmosphere (0.03%) the water removal is faster than the diffusion of CO_2 in the pores of the concrete conglomerate. The increase in CO_2 concentration inhibits the gas diffusion process due to the increase in water filling capillaries velocity, caused by the chemical reaction of CO_2 with the cement stone. According to the authors of the paper [7], the studies with a high concentration of CO_2 have shown that the results have some errors caused by concrete carbonation in vivo. The authors of the same paper found that in case of CO_2 concentration ($10 \pm 5\%$) the inhibition of the filling gas is not observed, in connection with which the test results for a given concentration have no inaccuracy.

The paper [15] presents the comparison of the experimental data obtained for the Portland cement concrete samples with the water-cement ratio of 0.8, 0.6 and 0.4 with the different CO_2 concentration (10 and 0.07%). The studies were carried out at a constant temperature of $200^\circ C$ and a relative humidity of 55% (normal mode). The results of the study provided for the accelerated testing and testing at conditions close to natural were processed using the calculation model of the form (4) which complies with the respective model of type (1):

$$y_d = \alpha_c \sqrt{t}, \quad (4)$$

where: y_d is the depth of carbonation, in mm; α_c is the coefficient of carbonation, mm/\sqrt{year} ; t -is the time, year.

Table 1 shows the carbonation coefficients for the accelerated carbonation testings α_c^1 and for the conditions close to natural

α_c^2 , as well as the coefficient $\eta = \frac{\alpha_c^1}{\alpha_c^2}$.

Table 1: Calculated carbonation coefficient (carbonation ratio) at various concentrations

Water-cement ratio	Concrete grade according to waterproofing qualities	Carbonation coefficient α_c^1 [mm \sqrt{year}] ($CO_2 = 10\%$) [11]	Carbonation coefficient α_c^2 [mm \sqrt{year}] ($CO_2 = 0.07\%$) [11]	$\eta = \frac{\alpha_c^1}{\alpha_c^2}$
0.8	< W2	79.1	10.8	7.32
0.6	< W4	51.2	6.8	7.53
0.4	W8	23.9	3.0	7.97

Table 1 shows, that η coefficient has a minimal deviation depending on the water cement ratio. It is noted in the paper [15] that the obtained ratio slightly increases at a low water-cement ratio; this means that the accelerated testing underestimates the resistance of the concretes with a low permeability to the carbonation. This fact is confirmed by the studies performed by Rosental N.K. [16], where it is noted that at low water-cement ratio the concretes with the carbon dioxide diffusion coefficient of $10^{-6} \text{ cm}^2/\text{s}$ can be obtained.

The concrete carbonation practically stops with this value of the diffusion coefficient.

The information above allows to conclude that the accelerated testing should be performed at the carbon dioxide concentration less than 10%; in case of accelerated testing of the concrete samples with permeability of W8 and less the deviation from the results obtained in vivo is possible.

For the purposes of the studies on carbonation of the samples (of the concretes different in density) the working hypothesis was adopted stating that in case of CO₂ concentration equal to 10%, the carbonation process is accompanied by the excess of gas. However, this process is controlled by the carbon dioxide diffusion only. Under natural conditions, the concentration of CO₂ is much lower-0.03%, i.e., the carbonation proceeds at CO₂ deficit, that is why the process is controlled by two parameters: the carbon dioxide diffusion and the chemical reaction. Given these differences, it was decided to take 5% as the working concentration of CO₂. At the same time there will be no significant excess of carbon dioxide, which brings the experiment to natural conditions.

To determine the rate of concrete carbonation the standard testing procedure, recommended by GOST R 52804-2007 [17] and EN 13295:2004 [18], was chosen. The prototype for the creation of the experimental installation was the engineering design by Rosenthal N.K. and Yazev V.K. [7]. The similar installation was presented in the paper [19].

The improved installation (Figure 1) consists of the following main parts: the sealed chamber (V = 0.2 m³), the cylinder with carbon dioxide; the gear unit; the automatic gas analyzer OKA-T-CO₂.

CO₂ is supplied to the tank through pipe installed in the tank cover. To prevent the pinpoint exposure of the CO₂ flows on the samples, the flexible hose with the upturned end is installed at the end of the pipe. The excess pressure in the chamber is discharged through the U-shaped pipe filled with water, mounted on the side wall.

To avoid the uneven concrete carbonation and mixing of the ambient air, the installation is equipped by the system of low-speed fans, installed inside the tank at the bottom along the contour.

According to the standard procedure [17] the required temperature and humidity conditions must be maintained into the sealed chamber, ie, the air temperature must be (20 ± 5)°C; and the relative humidity must be (75 ± 3)%. In order to ensure the constant temperature, the installation was mounted in a heated compartment. To create and maintain the relative humidity of the gas and air environment the glass bowl with a saturated NaCl solution was placed inside the sealed chamber. The batches of fine-grained concrete samples, the types and characteristics of which are given in the Table 2, were prepared for the testing. The average aluminate Portland cement of CEM II/A-III 32.5B grade with the content of mineral additives up to 20%, rapid-hardening, of 32.5 class (ZAO "Katavskiy cement") was taken as the binder for the preparation of the test samples. The quartz river sand from the Urshakskiy deposit of the Republic of Bashkortostan was chosen as the fine filler for the preparation of the test samples. The samples were prepared in the form of prism with the dimensions 40x40x160 mm. The molds were chosen taken into account the fact that the standard three-socket mold is

required to obtain the identical samples-the twins, made of the same compound with the same degree of compaction. The fine concrete prisms manufacturing technology included the following standard procedures: dosing of the binder, fine filler and water in the required proportion; mixing; molding; compaction on the vibrating table and exposure in the natural solidification camera during 28 days.

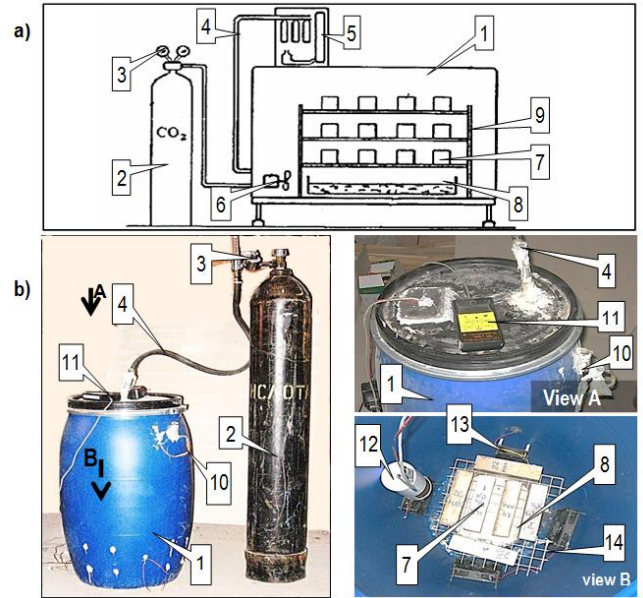


Figure 1: The installation for determination of the concrete carbonation kinetics. a-installation-the prototype developed by Rosenthal N.K. and Yazev P.V.; b-modified installation; 1-sealed chamber; 2-cylinder with CO₂; 3-gear unit; 4-flexible hose; 5-chemical gas analyzer; 6-domestic fan; 7-samples; 8-the cup with a saturated salt solution; 9-rack; 10-U-shaped pipe; 11-remote control of the automatic gas analyzer OKA-T-CO₂; 12-the sensor of the automatic gas analyzer installed inside the chamber; 13-the system of low-speed fans; 14-the grill to install the samples

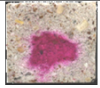
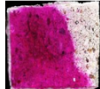
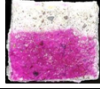

Table 2: Types and characteristics of the batches of samples produced

Batch No.	Composition	Comments
Type 1	Fine grain concrete (cement : sand=1:3 with W/C = 0.70)	porous concrete
Type 2	Fine grain concrete (cement : sand=1:3 with W/C = 0.65)	porous concrete
Type 3	Fine grain concrete (cement : sand=1:3 with W/C = 0.60)	concrete with normal permeability
Type 4	Fine grain concrete (cement : sand=1:3 with W/C = 0.55)	concrete with normal permeability
Type 5	Fine grain concrete (cement : sand=1:3 with W/C = 0.50)	concrete with normal permeability
Type 6	Fine grain concrete (cement : sand=1:3 with W/C = 0.45)	dense concrete

After exposure inside the natural hardening chamber (relative humidity equal to 100%), the samples were placed inside the chamber of the improved installation (relative humidity equal to 75%) and were exposed there until the achievement of the equilibrium humidity.

Before the experiment in order to avoid the impact of the edge effects, all facets, excluding the working one, were treated with the airtight material-paraffin. The selection of the working facet of the sample is of equal importance. According to the results of a preliminary study of the five grained concrete samples with the composition 1: 3 W/C = 0.60 (Table 3) it was revealed that the most uniform distribution of the concrete carbonation depth front arises in the upper and lower facets of the sample.

Table 3: Paraffin treatment options for the fine grained concrete samples with composition 1:3 W/C = 0.65 after exposure of 5% CO₂ (peeling by the section in 50 hours)

Sample treatment method	Photo-macrography of the sample	Average concrete carbonation depth, in mm.	rms deviation, %	Negative factors
without treatment		17.05	23.3	<ul style="list-style-type: none"> - The presence of the "edge effect", causing the significant deviation of the results; - The random "shift" of the healthy concrete zone's center, therefore it is impossible to measure the depth of concrete neutralization at the specified level; - The significant dependence on the technological factors (non-uniformity of the compression of the sample all over the section).
treatment of the lower, upper and one side facet.		16.38	13.2	<ul style="list-style-type: none"> - The dependence on the technological factors (compression of the mixture); - Non-uniform concrete neutralization rate over the section;
treatment of the lower and side facets.		15.47	4.8	<ul style="list-style-type: none"> - due to the increased porosity of the upper layer the rate of concrete neutralization is high (recommended by GOST [15])
treatment of the upper and side facets.		8.77	3.6	<ul style="list-style-type: none"> - due to the increased porosity of the upper layer the rate of concrete neutralization is low (recommended by GOST [15])

This fact indicates also that most structures "perceive" the aggressive environment either from the upper side or from the bottom side. The slabs and the coverings may be the examples of such structures. When the aggressive environment impacts from the upper side of the sample, the carbonation is more intense than in case of impact from the lower side. This phenomenon is explained by the fact that the upper layers of the test sample are of lower density, which leads to a high rate of concrete carbonation. This fact is confirmed by the results of the tests carried out on water absorption by weight (W_m). Therefore, for the upper layer, it amounts to $W_m = 8.25\%$, while for the lower layer it amounts to $W_m = 6.82\%$.

Table 3 shows that the most efficient for the study is the lower facet, as it actually corresponds to the claimed concrete grade according to waterproofing qualities.

After the treatment with the airtight material, the test samples were placed inside the sealed chamber. The test chamber was

sealed by the lid and was supplied with carbon dioxide to the desired concentration of 5%.

During the first five days of the experiment the absorption of carbon dioxide by concrete was intensive, that is why the concentration of carbon dioxide had to be maintained every two hours. Hereafter, the absorption of carbon dioxide stabilized and did not exceed 1% per day, which is valid in accordance with GOST R 52804-2007 [17].

After a certain period of time the sample was taken out and was sheared to determine the carbonation depth. The concrete carbonation depth was determined by the change in pH [7], the indicator-0.1% solution of phenolphthalein was applied on the fresh shear. The indicator changed its color from colorless in carbonized zone (pH 8.5) to magenta or purple in the non-carbonized zone (pH 11.5).

To monitor the concrete carbonation kinetics one and the same sample was sheared sequentially with a minimum interval of 15 mm from the previous shear. In about a minute the shear treated with indicator was photographed (macro photography). The camera lens was set strictly perpendicular to the axis of the sample to eliminate the factor of image distortion. To ensure this condition, a special tripod level was used.

Then the sample was retreated with the airtight material (paraffin) and replaced in the chamber for further carbonation. The resulting macro-photograph of the section was exported to the editing software and was scaled according to the actual size of the cross section. Then in the middle of the sample a plot of 10x20 mm was segregated in the photograph (Figure 2).

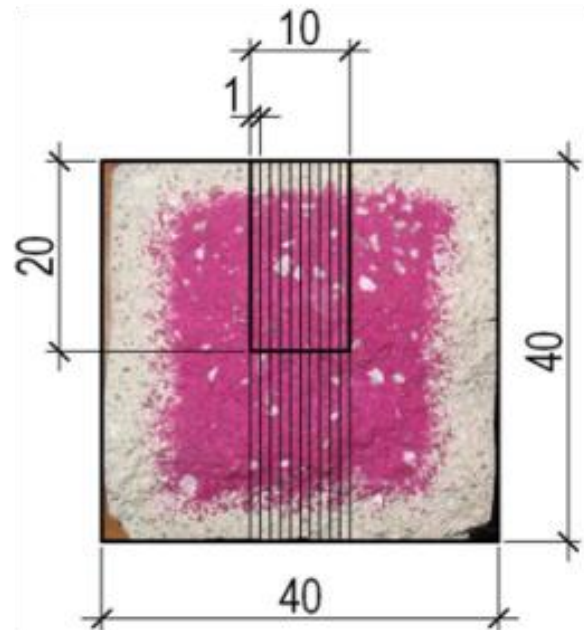


Figure 2: Determination of concrete carbonation depth by macro-photograph.

The carbonation depth of the sample in each section was calculated using the results of 10 measurements of one

selected zone. The measurement accuracy over the sections was 0.5 mm.

According to the guidelines for determining the carbonation depth of the samples, given in EN 13295:2004 [18], the following types of deviation of the carbonation front from the normal distribution, which were taken into account in the determination of a common front: the large corner effect; the wavefront; the local deep carbonation; the deviation from the front due to the presence of large pieces of thick filler; the deviation of the front due to the presence of fragments of porous filler.

The processing of the data obtained was performed by modern statistical methods in Statistica 6.0. software. Such processing resulted in the achievement of the average values with the upper limit in view of the Student coefficient of 0.95 (which corresponds to the requirements of GOST [17]).

DISCUSSION AND RESULTS

The results of experiments on kinetics of fine grained concrete carbonation are shown in Table 4 and Figure 3, the values of the coefficients A_y and n are shown in Table 5. The evaluation of the obtained mathematical models was carried out by regression analysis on the criterion-the maximum value of the convergence coefficient R^2 (determination coefficient). Figure 3 shows that the data obtained for all types of concrete can be described by a power function of the form (5):

$$L_y = A_y \cdot \sqrt[n]{t}, \tag{5}$$

where

L_y is the depth of concrete carbonation, in mm;

A_y is the coefficient of concrete samples carbonation during the accelerated testing, mm/(year)^{1/n};

t is the time interval from the beginning of the testing until the moment of shearing of the sample, in days.

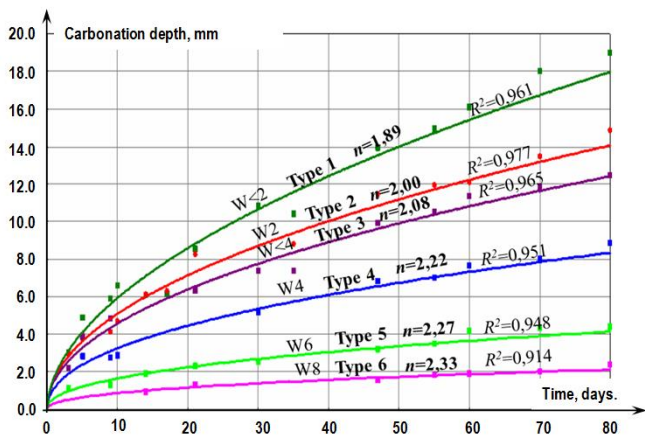


Figure 3: The carbonation rate of the fine grained concrete samples with composition 1:3 with different water-cement ratio

R^2 is the convergence coefficient (coefficient of determination)

The analysis of the data obtained (Figure 3) indicates that the concrete carbonation depth is determined by the density of the

samples, namely the porous fine grained concrete samples provide the clearly expressed dependence of carbonation degree on their density $n = 1.89 \dots 2.0$. Similarly, the samples of normal permeability and the dense samples show $n = 2.08 \dots 2.27$.

For the dense samples the exponent $n = 2.33$ significantly differs from the model of the form (1) wherein $n = 2$. This can be explained by the fact that the effect of inhibition of the CO_2 diffusion in dense concrete. This effect depends on the following three factors: the mechanical blocking of the diffusing substance flow by the dense (relatively impermeable) crystalline hydrate phase of the cement stone and the filler; the reduction of the effective section of the capillaries due to the presence of the boundary water layer, always present on the surface of the pores in the hygroscopic cement concrete; the tortuosity of the capillaries. More detailed description of CO_2 diffusion inhibition effect in concrete of dense and very dense permeability is given in the paper [16].

Table 4: The results of determination of the carbonation depth of the fine grained concrete samples

Sample batch number	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6
Water absorption, %	8.1	6.8	6.1	5.6	4.5	4.2
Concrete grade according to waterproofing qualities	<W2	W2	<W4	W4	W6	W8
Shear depth, in mm	0 10 20	0 10 20	0 10 20	0 10 20	0 10 20	0 10 20
Fragments of shears of the samples taken without time gaps, in days.	3, 5, 9, 10, 14, 17, 21, 30, 35, 47, 55, 60, 70, 80					

It is recommended to perform the transition from the experimental data obtained in the course of the accelerated testing to the natural operational conditions of concrete (at the carbon dioxide concentration in the environment equal to 0.03%-which corresponds to a clean area) by the formula (6):

$$A_n \approx A_y \cdot \sqrt[n]{\frac{C_{0.03\%}}{C_y}}, \tag{6}$$

where:

A_n -is the coefficient for natural conditions;

A_y -is the empirical coefficient obtained by the accelerated testing;

$C_{0.03\%}$ -is CO_2 concentration in natural operational conditions, %;

C_y -is CO_2 concentration in the accelerated carbonation testing (5%).

The results of determination of parameters A_y , A_n and n are given in the Table 5.

Table 5

Water-cement ratio W/C	Concrete grade according to waterproofing qualities W	Coefficient A_y , cm/day ⁿ	Coefficient A_n , cm/day ⁿ	Exponent n in the formula (2)
0.70	< 2	4.03	0.29	1.89
0.65	2	3.03	0.25	2.00
0.60	< 4	2.58	0.20	2.08
0.55	4	1.66	0.16	2.22
0.50	6	0.81	0.11	2.27
0.45	8	0.41	0.07	2.33

Figure 4 shows the dependence of the exponent n^{-1} on the water-cement ratio. As can be seen, the points obtained tend to a linear dependence of the form (6).

$$\frac{1}{n} = c \cdot d^{W/C} \quad (6)$$

where: $c = 0.29$ and $d = 2.35$ -are the empirical coefficients.

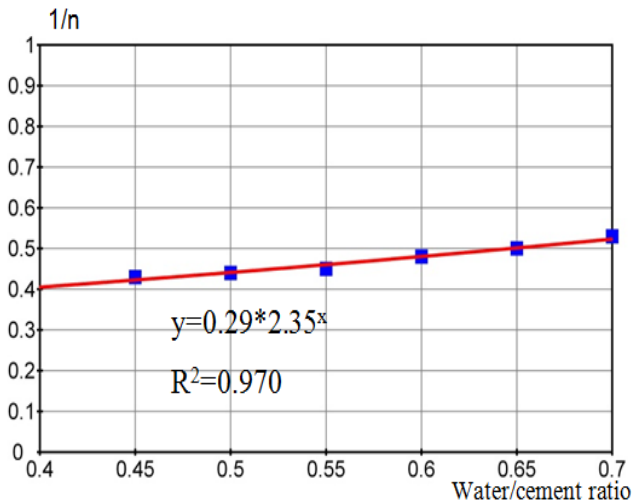


Figure 4: The dependence of the exponent n on the water-cement ratio W/C

In order to facilitate the usage of the calculated dependence of the form (7) by transformation, the graphs of dependence of the operational life of the structure (T) on the concrete grade

according to waterproofing qualities (W) in humid conditions were obtained (Figure 5).

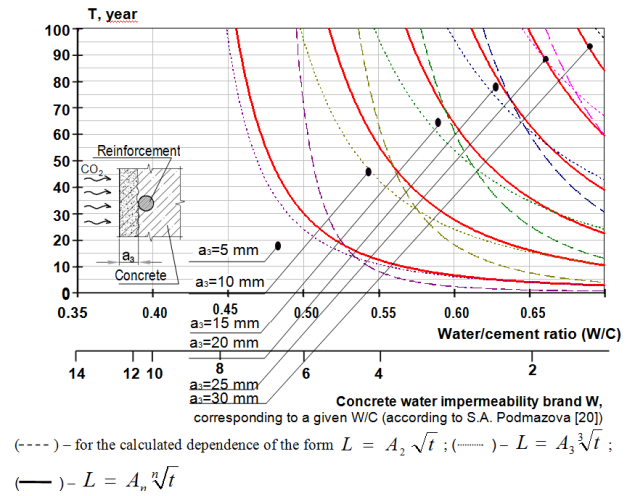


Figure 5: Dependence of the operational life of the structure (T) on the concrete grade according to waterproofing qualities (W) in humid operational conditions (at a relative humidity > 75%)

CONCLUSIONS

1. The experimental installation and the procedure for the studies on determination of the concrete carbonation for the accelerated testing with CO_2 concentration equal to 5% were developed.
2. It was found that the carbonation rate of the concrete can be described with the greatest reliability by the power function of the form $L=A_n \times t^{1/n}$ (where L is the carbonation depth, A_n is the carbonation coefficient), at the same time the exponent n is not constant and varies in dependence on the density of the sample: in porous concrete with waterproofing grade of $W_2 \dots W_4$ the value of n varies from 1.90 to 2.16, in $W_6 \dots W_8$ the exponent $n = 2.27 \dots 2.33$.
3. The engineering formula of the form (7) and the dependence of the operational life of the structure (T) from the concrete waterproofing grade (W) in humid mode of operation (at a relative humidity > 75%) was offered.

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REFERENCES

[1] History of Cement Static Content, n.d. Date Views 04.12.2015
www.cement.ca/en/content/History_of_Cement_Static_Content.html.

- [2] International Energy Statistics, n.d. Date Views 04.12.2015
www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=90&pid=44&aid=8.
- [3] Moskvina, V.M., 1969. To the Issue of Building Structures Durability. In Collected Papers CRCRI "Corrosion Protection of Building Structures and Increase of Their Longevity". Moscow: Stroyizdat, pp: 3-9.
- [4] EN 206-1. Concrete. Part 1. Requirements, Performance, Production and Conformity, 2000.
- [5] SNiP 2.03.11-85. Protection of Building Structures against Corrosion, 1986. Moscow: CISD Gosstroy USSR.
- [6] Hamada, M., 1968. Neutralization (Carbonation) of Concrete and Corrosion of Reinforcing Steel. In Proc. of the 5th International Symposium on Cement Chemistry, pp: 343-369.
- [7] Alekseev, S.N. and N.K. Rosental, 1976. The Corrosion Resistance of Reinforced Concrete Structures in Aggressive Industrial Environments. Moscow: Stroyizdat.
- [8] Papadakis, V.G., C.G. Vayenas and M.N. Fardis, 1989. A Reaction Engineering Approach to the Problem of Concrete Carbonation. Journal of the American Institute of Chemical Engineers, 1(11): 110-122.
- [9] Ishida, T., K. Maekawa and M. Soltani, 2004. Theoretically Identified Strong Coupling of Carbonation Rate and Thermodynamic Moisture States in Micropores of Concrete. Journal of Advanced Concrete Technology, 2(2): 213-222.
- [10] Liang, M., J. Wu and C. Liang, 2001. Multiple Layer Fuzzy Evaluation for Existing Reinforced Concrete Bridges. J. Infrastruct. Syst., 7(4): 144-159.
- [11] Gusev, B.V. and A.S. Fayvusovich, 2013. Mathematical Model of Atmospheric Corrosion of Concrete in view of Phase Transitions. Bulletin of Volgograd State University of Architecture and Civil Engineering. Construction and architecture, 31(2): 308-325
- [12] Latypov, V.M., A.R. Anvarov, E.V. Lutsyk, P.A. Fedorov and T.V. Latypova, 2015. Primary Protection of Reinforced Concrete against Impact of Carbon Dioxide. Oriental Journal of Chemistry, 1(31): 285-291.
- [13] Vandalovskaya, L.A., 1972. Investigation of the Processes of Corrosion of Reinforced Concrete Structures of the Spinning Mills in Viscose Production and the Development of Ways to Improve Durability, Author's abstract of a thesis for the degree of Candidate of Engineering Sciences, NIISK, Kiev.
- [14] Younsi, A., Ph. Turcry, A. Aït-Mokhtar and S. Staquet, 2013. Accelerated Carbonation of Concrete with High Content of Mineral Additions: Effect of Interactions between Hydration and Drying. Cement and Concrete Research, 43: 25-33.
- [15] Ishida, T., K. Maekawa and T. Kishi, 2003. Theoretically Identified Strong Coupling of Carbonation Rate and Thermodynamic Moisture States in Micropores of Concrete. Journal of Advanced Concrete Technology, 2(1): 91-126.
- [16] Rosental, N.K., 2006. Corrosion Resistance of Cement Concrete of Low and Very Low Permeability. Moscow: FSUE FPP.
- [17] GOST R 52804-2007. Protection against Corrosion of Concrete and Reinforced Concrete Constructions. Test Methods, 2009. Moscow: Publishing House FSUE "Standartinform".
- [18] EN 13295:2004. Products and Systems for the Protection and Repair of Concrete Structures. Test Methods. Determination of Resistance to Carbonation, 2004.
- [19] Papadakis, V.G., C.G. Vayenas and M.N. Fardis, 1991. Fundamental Modeling and Experimental Investigation of Concrete Carbonation. ACI Materials Journal, 4(88).
- [20] Podmazova, S.A., 2004. Quality Assurance of Concrete Monolithic Structures. Building Materials, 6: 8-9.