Comparative Research on Exploitation Frost Resistance of Ceramics and Concrete

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The aim of the work is to compare the influence of physical and structural parameters on the exploitation frost resistance for ceramics and concrete of walls and partitions. The physical and structural parameters of small effective porosity ($W_e \leq 26$ %) ceramics and concrete are determined: density (ρ), reserve of porous volume (R_p), capillary rate of mass flow (G), effective porosity (W_e) and exploitation frost resistance (F_E). Possibilities to predict the exploitation frost resistance of ceramics and concrete according to the indicated parameters are analysed. It is established that the exploitation frost resistance of small effective porosity ($W_e \leq 26$ %) ceramics and concrete may be predicted applying very similar empirical equations obtained. They justify analogous valid laws of exploitation factors affect for ceramics and concrete during exploitation.

Keywords: ceramics, concrete, exploitation frost resistance, empirical equations, physical and structural parameters.

1. INTRODUCTION

The exploitation frost resistance of porous building materials may be determined quite exactly applying the direct methods based on unilateral freezing principle. There is no doubt that exploitation conditions in walls or partitions of ceramic, silicate bricks, constructional concrete and other porous materials do not differ substantially in aspect of their frost resistance. In these constructions all items and materials are under the influence of directional, unilateral freezing, stronger or weaker atmospheric moisture and fluctuating cyclic temperature effect. However in that case exploitation conditions for various buildings may differ and using different products in constructions it is necessary to take into account their exploitation frost resistance grade [1].

On the ground of research on ceramic products, various concretes and finished structures performed in Lithuania and other countries [2 – 9] the new methods of exploitation frost resistance based on application of unilateral freezing principle are developed and standardised [10 – 13].

However investigations of various materials by direct methods last from few weeks to several months or years. Also the determinant for one or another grade of exploitation frost resistance of samples is not clear. Therefore importance of rapid prediction methods is increasing, especially of the methods providing results that allow prediction of frost resistance in exploitation conditions according to mechanical, deformational or specific physical parameters. This is due to the fact that frost resistance of ceramic and concrete products is not only the significant but also the very complex property, depending on the effect of atmospheric and exploitation factors and conditions [13 – 17], and on mechanical and physical-chemical features of the materials themselves [14, 18]. Although today a big attention is paid to the development of rapid prediction methods of exploitation frost resistance for ceramic materials [19 – 23], very few methods of that kind are created for concretes [21 – 24].

Advantage of the methods discussed allows not only the more rapid prediction of product exploitation frost resistance, but also the wider and deeper comparison of various materials properties. The steady traditional approach is that pores and capillaries of constructional ceramic body do not vary during exploitation and the porous structure of concretes (including gelic) changes essentially while hardening processes take place.

Theoretically [25] the porosity of the modelling medium from the like spherical particles depends on the packing of these particles. For the cubic pack, its porosity is 47.64 %, and for the limit hexagonal pack – 25.95 %. In the last-mentioned case rhomboidal pores reach 18.58 %, and tetrahedral – 7.37 %. Namely the pack of the particles determines the pores` radius, their maximum and minimum values.

Forecasting the exploitation frost resistance of ceramics the division of samples according to the limit parameter of effective porosity 26 % is widely applied. It is determined [2, 14] that with the increasing or decreasing parameter (from the limit value) the parameters of exploitation frost resistance of ceramics usually increase further on. Therefore it may be assumed that this law is valid for the concretes as well. It should be noted that due to the structure complexity of materials with smaller effective porosity (≤ 26 %) the development of rapid prediction methods of exploitation frost resistance is complicated. Therefore this problem is relevant also for the concretes with the mentioned small effective porosity. Furthermore, the parameter of effective porosity W_e itself has not been applied yet even in the empirical equations for ceramics, forecasting the exploitation frost resistance.

It was not possible to find the results of comparative investigations in the scientific literature that would prove the possibility to predict the exploitation frost resistance of ceramics and concrete according to the same structural, mechanical and deformational parameters.

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Table 1. Characteristics of physical and structural parameters

Notation	Name of parameter and dimension	Calculation formulas	Description of components of the main parameter and dimensions
x_1	Density, kg/m^3	$\rho = \frac{m_0}{V}$	m_0 – mass of sample dried to the constant mass, kg V – volume of water saturated sample, m^3
x_2	Reserve of porous volume, %	$R_p = \left(1 - \frac{W_e}{W_p}\right) \cdot 100$	W_e – effective porosity according to water absorption after 72 h, % W_p – total open porosity according to water absorption by vacuuming (special regime), %
x_3	Effective porosity, %	$W_e = \rho \frac{m_1 - m_0}{m_0} 100$	P – sample density, g/cm^3, m_1 – mass of sample saturated in normal conditions, g m_0 – mass of sample dried to the constant mass, g
x_4	Capillary rate of mass flow, g/cm^{2}h	$G = \frac{m_1 - m_0}{S}$	m_1 – mass of sample saturated by capillary suction, g m_0 – mass of sample dried to the constant mass, g S – area of sample working surface, cm^2

The aim of this work was to clear up and to analyse in more details the possibilities to predict the exploitation frost resistance of ceramics and concrete according to the parameters of density ρ, reserve of porous volume R_p, capillary rate of mass flow G and effective porosity W_e when effective porosity of materials is less than 26 %.

2. MATERIALS, INVESTIGATION METHODS AND EQUIPMENT APPLIED

To reach a goal we sought to produce the samples of ceramics and concrete with the same set of structural parameters values and exploitation frost resistance
From the six batches of each material produced for that purpose in the laboratory conditions we selected five samples of ceramics (70×70×70 mm) and five samples of concrete (100×100×100 mm) from each batch.

Ceramic samples were formed in a plastic way applying clay of Rokai mine, firestone, sand, anthracite, peat, grind bottle glass, and varying their quantities. These raw materials were dried, crushed, sieved and mixed manually. The samples formed were dried in the electric stove in the temperature (105 ±5) °C. Dried samples were burned in the oven for 24 hours, keeping the maximum temperature 1080 °C for 3 hours.

The raw materials for concrete samples: binding material – cement 42.5 R, aggregates – sand, gravel, breakstone. The aggregates were prepared in the same way as for ceramics, after that they were mixed dry with cement. The samples were formed in the pressing forms, applying vibration and further on keeping them in the moist medium for the normative time. The samples differed by the quantity and proportion of components, water cement ratio and other conditions.

General characteristics of parameters by which the properties of ceramic and concrete samples were analysed are presented in Table 1. The methodology for determination of these parameters is discussed in literature [9, 14, 26].

The laboratory investigations determining the frost resistance of ceramics and concrete by unilateral freezing were performed in the standard freezing and moistening device [11] installing the testing fragment, the principal scheme of which is presented in Fig. 1. In order the thickness of ceramic and concrete fragments would be the same (100 mm), the ballast ceramic (thickness 30 mm) was applied additionally to ceramic samples from the inner side.

The fragment was frozen and thawed out according to the regime provided in the concrete standard [11].

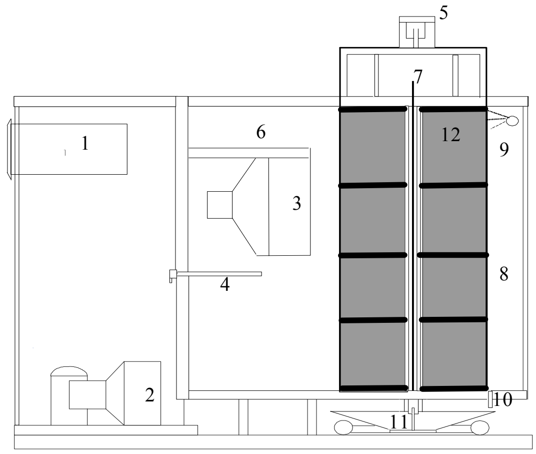

Fig. 1. Principal scheme of freezing – moistening device: 1 – management – commutation apparatus with a self-recording – potentiometer; 2 – freezing aggregate; 3 – evaporator with a ventilator; 4 – resistance thermometer; 5 – moving frame; 6 – freezing chamber; 7 – rotational sample sections, separated by a metal partition; 8 – thawing – moistening section with a transparent cap; 9 – water sprayer; 10 – gap for pouring out the water with a valve; 11 – water collector-deflector; 12 – samples in the testing fragment

Destruction of ceramics and concrete was evaluated according to its prime cycle by criteria applying disintegration of any kind: cracking, splitting, fracturing, crumbling.

The investigation results obtained were processed applying methods of mathematical statistics [27].

The limit effective porosity assigned for ceramic and concrete samples is less or equal to 26 %. By preliminary investigation it is determined that the effective porosity of the ceramics and concrete under investigation was less than 26 %. According to this parameter histograms are formed (Fig. 2). It is determined that the distribution is normal and the data is adequate as their density functions are very similar. This enables to state the sufficient

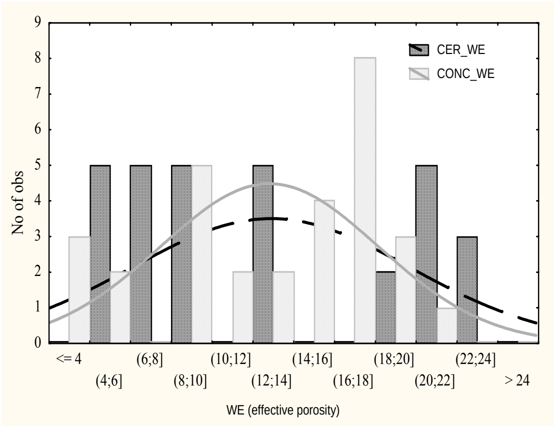

Fig. 2. Histogram of effective porosity of ceramics and concrete: *CER-WE* (effective porosity of ceramics) = 30×2×normal (x; 12.88; 6.83); *CONC-WE* (effective porosity of concrete) = 30×2×·normal (x; 12.81; 5.34)

sameness of the materials under investigation (by this parameter).

3. EXPERIMENTAL RESULTS

We have subdivided the research results into two groups. At first we will analyse the investigation results of ceramics, later the ones of concrete.

3.1 Results of ceramics investigation

The calculated average values of physical and structural parameters, including the experimentally obtained value of exploitation frost resistance (in cycles) are presented in Table 2, and the analogous characteristic values in Table 3.

Table 2. Average values of physical and structural parameters of ceramics

No. of batch	ρ (x_1), kg/m^3	R_p (x_2), %	W_e (x_3), %	G (x_4), g/cm^2·h	F_E (y), cycles
1	1752	43.64	20.42	0.336	38
2	1724	39.56	22.75	0.514	25
3	2022	65.75	6.58	0.066	112
4	1920	49.15	13.28	0.196	76
5	2246	71.15	5.24	0.018	140
6	2170	48.62	9.02	0.198	100

After determining the before-mentioned parameters, the pair correlation matrix of parameters is formed (Table 4). It shows the relation and the variation trends by the obtained parameters values. After proving that there is a strong correlation between the analysed parameters and the exploitation frost resistance, the empirical equation (1) is obtained. The significance of equation variables (according to the Stjudent criteria, if the values are bigger than the ones in tables, the regression coefficient is said to be significant), multiple correlation coefficient (numerical characteristics evaluating linear interdependence) [27], determination coefficient (numerical characteristics evaluating model suitability) and standard deviation are presented in Table 5 and Table 6.

Table 3. Characteristic values of physical and structural parameters of ceramics

No. of batch	ρ (x_1), kg/m^3	R_p (x_2), %	W_e (x_3), %	G (x_4), g/cm^2·h	F_E (y), cycles
1	1730	42.43	21.45	0.370	34
1	1770	45.06	19.21	0.310	43
2	1710	36.17	23.64	0.800	23
2	1750	38.54	21.12	0.370	28
3	2000	64.26	7.61	0.06	108
3	2050	66.29	5.92	0.11	117
4	1910	47.56	13.64	0.13	74
4	1930	50.54	13.09	0.26	78
5	2220	70.20	6.02	0.03	135
5	2280	72.76	4.21	0.01	144
6	2150	45.66	9.47	0.31	95
6	2180	51.12	8.12	0.12	109

Table 4. Pair correlation matrix of parameters

Para-meters	x_1	x_2	x_3	x_4	y
x_1	1.00	0.76*	–0.93*	–0.77*	0.95*
x_2	–	1.00	–0.87*	–0.86*	0.92*
x_3	–	–	1.00	0.87*	–0.98*
x_4	–	–	–	1.00	–0.88*
y	–	–	–	–	1.00

Remark: *– the parameter is significant

$$y = -90.3 + 0.07x_1 + 1.02x_2 - 2.08x_3 - 11.1x_4 . \quad (1)$$

As not all parameters are significant (the parameter is significant when the value of Stjudent criteria is bigger than the value in table 2.04) for the exploitation frost resistance parameter, we derive the optimal empirical equation (2). In this case the accuracy of prediction slightly decreases, as well as duration of investigation.

$$y = -93.61 + 0.07x_1 + 1.10x_2 - 2.24x_3 . \quad (2)$$

Multiple correlation, determination coefficients, standard deviation and Stjudent criteria of the derived equation (2) are presented in Tables 5 and 6.

From the Table 5 we can see that the values of multiple correlation and determination coefficients, as well as standard deviation varied only very little, therefore predicting the exploitation frost resistance it is advisable to use the optimal empirical equation (2).

The empirical equations (1) and (2) also confirm the laws known for ceramics: decreasing the values of parameters W_e and G the values of material F_E increase when the effective porosity is smaller than 26 %. Whereas the bigger is the reserve of porous volume and material density (either the walls of pores and capillaries are thicker), the bigger is the exploitation frost resistance, irrespective to the effective porosity values [2, 14].

Table 5. Multiple correlation, determination coefficient and standard deviation of the empirical equations (1), (2)

No. of equation	Multiple correlation coefficient, R	Determination coefficient, R^2	Standard deviation s_e, cycles
1	0.998	0.996	2.94
2	0.998	0.995	3.04

Table 6. Stjudent criteria for empirical equations (1), (2)

No. of equation	Stjudent criteria for:			
	Density, t_ρ	Reserve of porous volume, t_{Rp}	Effective porosity, t_{We}	Capillary rate of mass flow, t_G
1	9.90	9.39	9.73	1.69
2	9.51	10.69	7.35	–

According to the Stjudent criteria values of the optimal equation (2) it is seen (Table 6) that exploitation frost resistance is mostly affected by reserve of porous volume, density and effective porosity. The bigger is the reserve of porous volume and density and the smaller is the effective porosity, the bigger is the exploitation frost resistance.

Comparison of the experimental and theoretical values of exploitation frost resistance calculated by equation (2) is presented in Fig. 3. These results visually justify the big accuracy of prediction.

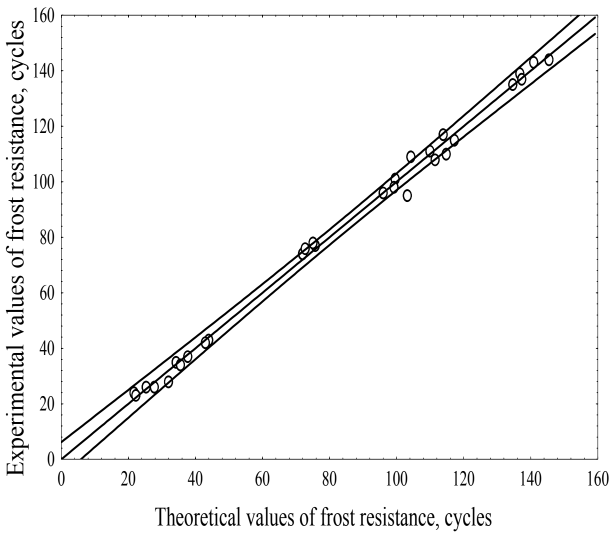

Fig. 3. Comparison of theoretical and experimental values of ceramics exploitation frost resistance

The average values of ceramic batch parameters presented in Table 2 are in principle from the same set as the concrete samples (Table 8).

3.2 Results of concrete investigation

Analogous results obtained for concretes are presented in Tables 7 and 8. The characteristic values of density and structural parameters and the experimentally obtained exploitation frost resistance in cycles are presented in Table 7. Table 7 shows that the reserve of porous volume of the selected concrete samples varied from 22.41 % to 72.15 %; capillary rate of mass flow from 0.012 to 0.761.

From the data presented in Table 9 it follows that the relation between exploitation frost resistance of concrete and the other parameters determined is also quite strong.

Table 7. Characteristic values of physical and structural parameters of concrete

No. of batch	ρ (x_1), kg/m^3	R_p (x_2), %	W_e (x_3), %	G (x_4), g/cm^2·h	F (y), cycles
1	2180	30.21	14.45	0.221	55
1	2280	36.25	8.75	0.180	61
2	2360	39.45	12.32	0.134	64
2	2410	43.71	8.87	0.124	70
3	2830	68.01	4.73	0.012	155
3	2880	72.15	3.46	0.018	168
4	2210	22.56	18.88	0.559	38
4	2390	30.95	14.02	0.200	51
5	2420	24.55	17.94	0.573	39
5	2470	28.09	15.88	0.341	51
6	2530	22.41	20.12	0.761	35
6	2640	26.54	16.84	0.501	44

Table 8. Average values of physical and structural parameters of concrete

No. of batch	P (x_1), kg/m^3	R_p (x_2), %	W_e (x_3), %	G (x_4), g/cm^2·h	F_E (y), cycles
1	2224	33.00	10.37	0,200	58
2	2380	41.34	10.65	0.130	67
3	2852	67.96	3.95	0.015	162
4	2294	25.52	16.23	0.360	43
5	2452	25.84	17.09	0.492	44
6	2570	24.29	18.56	0.637	39

Table 9. Pair correlation matrix

Parameters	x_1	x_2	x_3	x_4	y
x_1	1.00	0.68*	–0.39*	–0.15	0.75*
x_2	–	1.00	–0.90*	–0.80*	0.98*
x_3	–	–	1.00	0.92*	–0.88*
x_4	–	–	–	1.00	–0.73*
y	–	–	–	–	1.00

Remark: *– the parameter is significant

Processing results of these investigations statistically, such empirical dependence of parameter (y) on structural characteristics of concrete is obtained:

$$y = -93.3 + 0.06x_1 + 1.40x_2 - 2.34x_3 - 3.84x_4 \ . \quad (3)$$

The values of Stjudent criteria, multiple correlation coefficient, determination coefficient and standard deviation of the derived equation (3) are presented in Tables 10 and 11.

Processing results of these investigations statistically, the optimal empirical dependence of parameter (y) on density and structural characteristics of concrete is obtained:

$$y = -89.6 + 0.06x_1 + 1.45x_2 - 2.40x_3 \ . \quad (4)$$

From the data in equation (4) one can see that exploitation frost resistance in cycles depends on density, reserve of porous volume and effective porosity. The bigger is density and reserve of porous volume and the smaller effective porosity, the bigger exploitation frost resistance in cycles.

As we can see from the dependence of exploitation frost resistance and effective porosity, capillary rate of mass flow, density and reserve of porous volume (equation 3), the same laws are valid for concrete as the ones for ceramics.

Comparison of the theoretical (calculated according to empirical equation (4)) and the experimental values presented in Fig. 4 justifies the big prediction accuracy.

From the data presented in Tables 10 and 11 it also follows that applying the optimal equation (4) the accuracy of prediction almost does not change.

It is proved that the exploitation frost resistance of quite small effective porosity ceramics and concrete depends on the values of the analysed set of ceramics and concrete structural and density parameters. The close and negative values of the free member in equations (1) – (4) enable to make an assumption that in this case the porous structure of both materials is also very close in a qualitative meaning. In the opposite case the situation may change.

Table 10. Multiple correlation, determination coefficients and standard deviation of the empirical equations (3), (4)

No. of equa-tion	Multiple correlation coefficient, R	Determination coefficient, R^2	Standard deviation, s_e, cycles
3	0.988	0.977	7.14
4	0.988	0.977	7.00

Table 11. Stjudent criteria for empirical equations (3), (4)

No. of equa-tion	Stjudent criteria for:			
	Density, t_ρ	Reserve of porous volume, t_{Rp}	Effective porosity, t_{We}	Capillary rate of mass flow, t_G
3	3.13	3.18	2.62	0.71
4	9.51	10.69	7.35	-

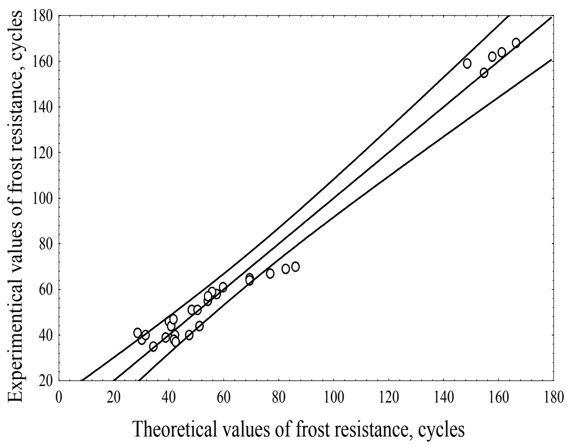

Fig. 4. Comparison of theoretical and experimental values of concrete exploitation frost resistance

Despite the fact that pair correlation between the discussed parameters is very embodied, the possibilities to predict the exploitation frost resistance of constructional concrete and ceramics according to the density and structural parameters of samples by elementary empirical equations is proved.

CONCLUSIONS

1. Optimal empirical equations for prediction of exploitation frost resistance of ceramics and concrete have been derived.
2. It has been determined that exploitation frost resistance of ceramics and concrete depends mostly on density, reserve of porous volume and effective porosity. Physical interpretation of empirical equations is the following: the bigger is the density and the reserve of porous volume and the smaller is the effective porosity of the porous material, the bigger is the exploitation frost resistance of ceramic and concrete products.
3. Performing the comparative investigation, it has been determined for the first time that the same laws are valid for ceramics and concrete in aspect of exploitation frost resistance.

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