Predicting Frost Resistance of Concrete with Different Coarse Aggregate Concentration by Porosity Parameters

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Frost resistance is one of the key indicators of concrete quality. Frost resistance can be determined by direct testing; however it is time-consuming and labour-intensive method. Concrete decomposition is a complex process (from initial signs of degradation to complete failure of the surface subjected to freezing) involving many factors. Frost resistance of concrete can be predicted from porosity parameters after determining their relation to frost resistance. Test results showed the relation between the closed porosity of concrete and frost resistance factor. Closed porosity of concrete was found to have a significant influence on frost resistance factor. It is shown that closed porosity depends on the concentration of coarse aggregate in concrete, the closed porosity and predicted frost resistance of concrete increase with lower concentration of coarse aggregate.

Keywords: concrete, water absorption, coarse aggregate concentration, porosity parameters, frost resistance factor.

INTRODUCTION

Recently durability and serviceability have been given the biggest attention in the field of cementitious materials. Degradation of concrete due to freezing and thawing is the most common case of deterioration of concrete structures. Frost resistance of concrete depends on material structure, namely porosity, the size of pores and capillaries, pore size distribution and type (open and closed pores), and is one of many parameters that can be used to define the durability of concrete [1 – 3].

Concrete is a porous substance. Capillary pores in concrete are formed with the removal of excess water. The pores are open and therefore easily absorb water. Entrapped air voids are formed during concrete mixing, and they are closed. Open pores impair, whereas air voids improve frost resistance of concrete [4 – 6].

Frost resistance of concrete depends both on open porosity (the amount of capillary pores), and on closed porosity (air content in the mixture), and quantitatively can be determined by the frost resistance factor *KF*, which is derived from the equation [7]:

$$K_F = \frac{P_u}{0.09\,P_a}\,, \qquad (1)$$

where: P_u is closed porosity of concrete; P_a is open porosity of concrete.

There are four types of pores in concrete. These are: (a) gel pores, (b) capillary pores of the size (5 – 5000) μm; (c) macro pores resulting from entrained air, and (d) macro pores resulting from insufficient compaction. Gel pores, the common size of (1.5 – 2.0) μm, have no negative effect on concrete strength due to porosity; however they directly affect creep and shrinkage of concrete. Capillary pores and other coarse pores reduce concrete strength and elasticity [8 – 10].

It is generally accepted that low water/cement ratio and good setting conditions are important for obtaining frost resistant concrete products [11 – 13].

Pore size and distribution enable to determine potential deterioration of concrete structures. These parameters also enable to determine how much water will be absorbed [14]. T. C. Powers and his colleagues T. L. Brownyard were the first researchers who investigated concrete subjected to freeze-thaw cycles. They hare shown that concrete durability depends on the structure, capacity, radius, size and spacing of pores [9].

According to H. Cai and X. Liu [10], the capillary pores are smaller in size in stronger concretes compared to ordinary concretes. In reality, concrete hardly ever becomes completely saturated because some pores are barely reached by water. The saturation limit of 0.917 is based on the volume of ice being 9 % larger than water. Experimental research, described in detail by G. Fagerlund, has proved that concrete fails at lower degree of saturation [11].

The amount of capillary pores in cement stone mainly depends on free water content and the degree of hydration. Higher w/c ratio and the content of free water in cement stone lead to bigger amount of capillary pores [15 – 16].

Frost resistance of concrete is impaired by open pores and capillaries, which are formed by evaporation of free water. The amount of such pores and capillaries depends on w/c ratio. The more water is used in the cement mix, the more free water remains thus forming the bigger amount of open pores by evaporation [10].

The need to control porosity parameters and entrained air content was determined in the construction of concrete structures used in road building. Besides, frost resistance requirements for these elements are more demanding with respect to the application of concrete structures [2].

Frost resistance of concrete mainly depends on its capillary porosity and air content. These parameters can be controlled in the process of concrete production provided that concrete will be subjected to freeze-thaw cycles [8].

This paper mainly aims at finding out and exploring the possibility of predicting the frost resistance of concrete by porosity parameters.

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MATERIALS AND TEST METHODS

The concrete mix was produced from natural materials, and by composition and selected aggregates it complied with the requirements applicable to concrete mix with regard to consistency, density, strength, durability, anticorrosive protection of steel, production process and concrete laying procedures.

The concrete mix was made of water, cement, natural sand and coarse aggregate, namely gravel, stone chips. Coarse aggregates are the main and the most important elements in the composition of concrete mix. Concrete compositions differed by the amount of cement, gravel and water, which mainly determine the properties of concrete. Portland cement produced in JSC „Akmenės cementas" was used. Specimens were made of CEM I 42.5 N class Portland cement complying with LST EN 197-1:2000 standard. Sand was obtained from Kvesai quarry (average density 2653 kg/m³) outside Kaunas. Gravel was obtained from Vilijampolė quarry (fraction 4/16 mm). Stone chips were obtained from Kvasai quarry (fraction 4/16 mm). Potable water of room temperature was used for the production of concrete mix. Concrete composition and technological properties (slump, density, air content) are presented in Table 1.

Dry aggregates were used to prepare concrete mixes. Cement and aggregates were dosed by mass, whereas water was dosed by volume.

Concrete cubes (10×10×10 cm) of 12 compositions different in cement, aggregate and water content were formed to determine the properties of concrete. The specimens were compacted on laboratory vibration table, removed from formwork 24 hours after casting and cured for 28 days in a standard curing chamber (at 20 °C). Prior chamber and kept for 24 hours at room temperature.

The concentration of coarse aggregate φ_{st} in concrete was derived from the equation:

$$\varphi_{st} = \frac{S_t}{\rho_{st}}, \tag{2}$$

where S_t is the coarse aggregate content in concrete: ρ_{st} is the coarse aggregate density.

The total porosity of concrete was determined by concrete density, whereas open porosity was determined by the total water saturation. Concrete porosity indicators – average size of open capillary pore λ and open capillary pore size uniformity α – were determined from the kinetics of water absorption (GOST 12730.4-78).

Concrete slump and density were tested according to EN 12350-2, EN 12350-6. Entrained air content was calculated from fresh concrete density and constituent materials densities:

$$P = \left[1 - \left(\frac{C}{\rho_c} + \frac{S_m}{\rho_{Sm}} + \frac{S_t}{\rho_{St}\left(1 + \frac{W_{St}}{100}\right)} + \frac{V - \frac{W_{St} \cdot S_t}{100}}{\rho_v}\right)\right]100, \tag{3}$$

where C, S_m, S_t, V are the concrete, coarse aggregate content, sand, water in concrete; ρ_c, ρ_{sm}, ρ_{st}, ρ_v are the concrete, coarse aggregate content, sand, water density.

Test results were processed by using mathematical statistics methods [17].

EXPERIMENTAL RESULTS

Absorption of concrete specimens increases with the bigger amount of open and capillary pores, which are formed by evaporation of free water. The amount of such pores and capillaries depends on w/c content. The more water is used in concrete mix, the more of it remains unbound and thus the amount of capillary pores becomes bigger with evaporation of water. Therefore, low w/c ratio not only improves concrete strength, but also improves its durability and resistance to freeze-thaw cycles.

Tested concrete specimens exhibited different water absorption. Kinetics of water absorption in specimens C16/20 (small strength), C25/30 (average strength), C45/50 (high strength) is presented in Figures 1, 2, and 3.

Presented results (Figs. 1 – 3) show that with the change of coarse aggregate concentration from 0.46 to 0.23, water absorption remains similar because water content in the cement mix is the same. In sand-concrete specimens (concrete without coarse aggregate) water absorption is higher (about 1 %) because water content in this concrete is higher compared to aforementioned concretes.

Table 1. Concrete compositions and technological properties

Concrete	Specimen No	Content of materials in 1m³ of concrete, kg				Concrete mix			
		Cement	Gravel	Sand	Water	Density, kg/m³	Air content, %	Slump, cm	w/c
C16/20	1.1	248	1203	771	178	2400	0.72	5.0	0.72
	1.2	238	909	1037	172	2356	2.52	1.5	0.72
	1.3	261	614	1254	183	2312	3.44	0.5	0.70
	1.4	337	0	1670	213	2220	5.08	0	0.63
C25/30	2.1	347	1188	685	184	2404	0.81	7.0	0.53
	2.2	336	889	957	178	2360	2.58	2.5	0.53
	2.3	359	599	1189	185	2332	3.13	1.0	0.52
	2.4	486	0	1557	207	2250	5.14	0	0.43
C45/50	3.1	461	1193	573	179	2409	1.56	3.5	0.39
	3.2	438	897	881	169	2388	2.67	1.0	0.39
	3.3	465	598	1112	176	2354	3.47	0.5	0.38
	3.4	555	0	1536	194	2288	4.95	0	0.35

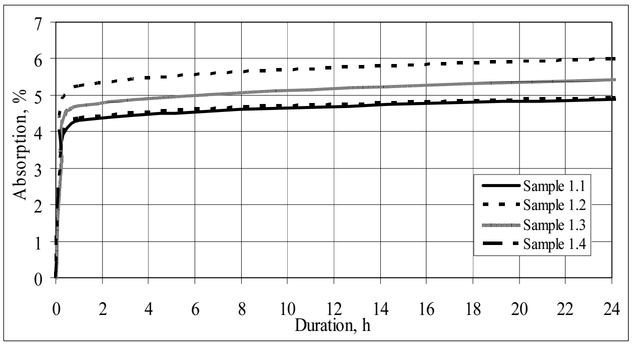

Fig. 1. Function of absorption and time in C16/20 concrete specimens

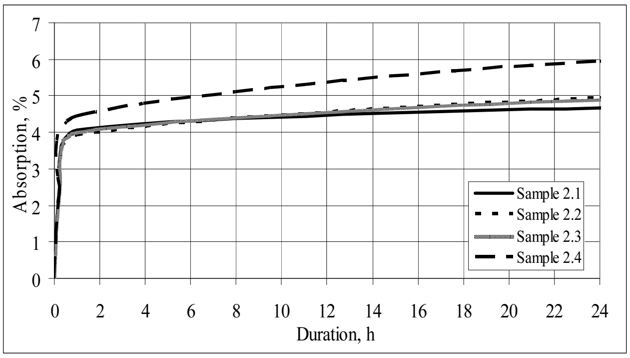

Fig. 2. Function of absorption and time in C25/30 concrete specimens

Presented results reveal that C16/20 concrete specimens reached permanent absorption after 5 hours of soaking due to coarser capillary pores in the cement mix. Therefore, the rate of absorption was higher compared to other tested concretes.

Specimens of average strength concrete reached permanent absorption after 11 hours of soaking, whereas specimens of C45/50 concrete reached permanent absorption after 21 hours of soaking because capillary pores of this concrete are finer and therefore absorption rate is lower.

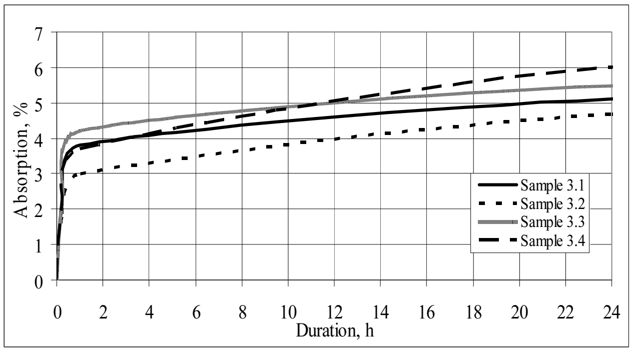

Fig. 3. Function of absorption and time in C45/50 concrete specimens

Presented results (Figs. 1 – 3) reveal that absorption rate increases in concrete specimens with coarser capillary pores.

The concentration of coarse aggregate and porosity and frost resistance factor parameters in concrete specimens were determined during testing. They are presented in Table 2.

With lower concentration of coarse aggregate, the pore average size indicator λ goes down (Table 2). This means that concretes with lower coarse aggregate content have smaller pores and such concrete has better frost resistance. Pore size uniformity indicator α is almost the same in concretes with different coarse aggregate concentration (Table 2). This means that concretes with different coarse aggregate concentration have almost the same pore size distribution.

The work revealed no changes observed in the samples was therefore estimated the pore average size indicator λ on frost resistance factor.

The function of porosity and coarse aggregate concentration in low, medium and high strength concretes hardened under natural conditions is presented in Figs. 4 – 6.

Closed porosity of concrete significantly affects concrete's frost resistance factor, and it largely depends on the concentration of coarse aggregate in concrete (Figs. 4 – 6).

Table 2. Concretes of different porosity characteristics

Concrete	Specimen No.	φ_{st}	Specific concrete density, kg/m³	Density, kg/m³	Frost resistance factor, K_F	Concrete porosity , %			Porosity indicators	
						total	open	closed	λ	α
C16/20	1.1	0.46	2664	2336	0.78	12.31	11.14	1.17	3.31	0.60
	1.2	0.35		2290	2.21	14.04	11.60	2.44	3.36	0.62
	1.3	0.24		2251	3.42	15.50	12.22	3.28	3.43	0.64
	1.4	0		2147	4.91	19.41	13.66	5.75	3.07	0.67
C25/30	2.1	0.46	2646	2344	0.57	11.41	11.18	0.23	2.74	0.60
	2.2	0.34		2298	2.25	13.15	10.93	2.22	1.90	0.60
	2.3	0.23		2260	3.78	14.59	11.17	3.42	2.26	0.62
	2.4	0		2165	5.07	18.18	12.63	5.55	1.60	0.64
C45/50	3.1	0.45	2678	2321	1.61	13.33	11.66	1.67	1.92	0.59
	3.2	0.34		2323	2.19	13.26	10.84	2.42	1.23	0.51
	3.3	0.23		2281	2.63	14.82	11.91	2.91	1.43	0.60
	3.4	0		2231	3.21	16.69	13.20	3.49	0.95	0.60

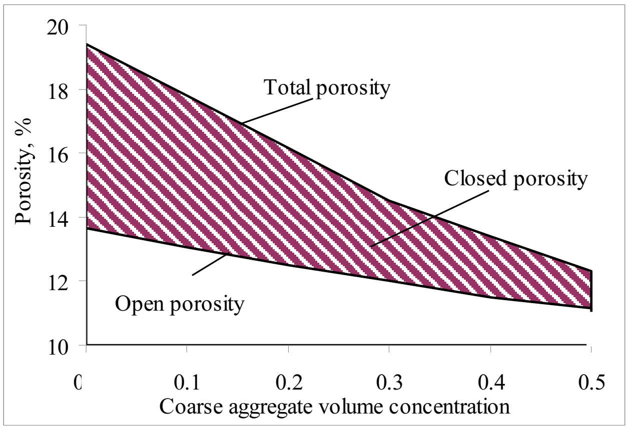

Fig. 4. The function of porosity and coarse aggregate concentration in C16/20 concrete hardened under natural conditions

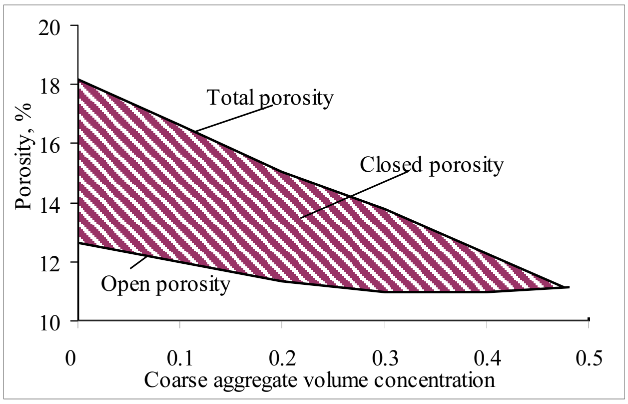

Fig. 5. The function of porosity and coarse aggregate concentration in C25/30 concrete hardened under natural conditions

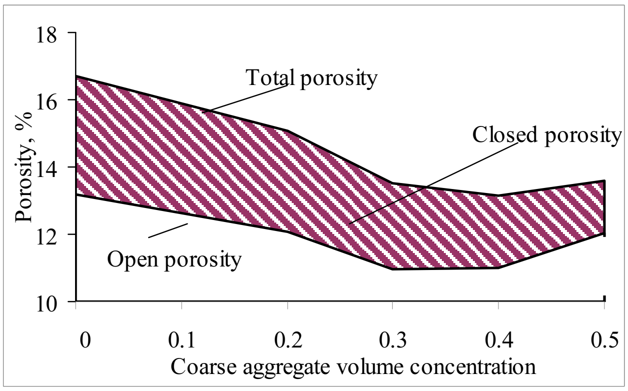

Fig. 6. The function of porosity and coarse aggregate concentration in C45/50 concrete hardened under natural conditions

Therefore, lower concentration of coarse aggregate increased closed porosity and concrete's resistance to freezing. The smaller size of pores also improves frost resistance factor.

The tests have revealed that the longer it takes for the open pores and capillaries to absorb water and the higher is the degree of absorption and the lower closed porosity, the poorer is frost resistance factor of concrete.

Statistical processing of test results have shown that there is no dependence of open capillary pore size uniformity indicator α on the frost resistance factor K_F.

The correlation coefficient of the function is 0.567, and the determination coefficient is 0.322 (Fig. 7).

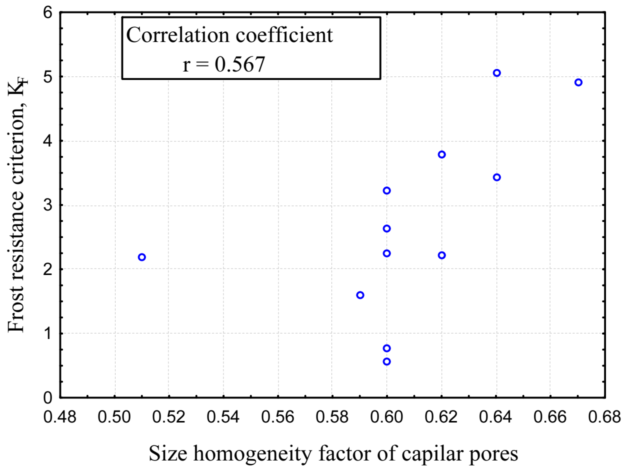

Fig. 7. Function of frost resistance factor and size homogeneity factor of capillary pores

The test results have shown that open capillary pore size uniformity indicator has little effect on frost resistance factor.

Statistical processing of test results by using a linear function model produced a function (Fig. 8) of coarse aggregate concentration (φ_{st}) and frost resistance factor (K_F). The correlation coefficient of the function is –0.902, and the determination coefficient is 0.814. The following empirical equation was produced:

$$K_F = 4.6 - 7.3 \cdot \varphi_{st} \,. \tag{4}$$

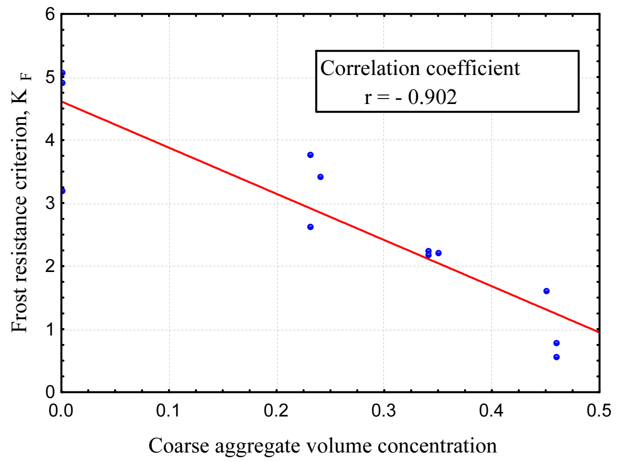

Fig. 8. Function of frost resistance factor and coarse aggregate volume concentration

The test results have shown that the frost resistance factor depends on the concentration of coarse aggregate. The lower is coarse aggregate concentration, the higher is frost resistance factor and the better resistance of concrete to freezing.

Statistical processing of test results by using a linear function model produced a function (Fig. 9) of closed porosity (P_u) and frost resistance factor (K_F). The correlation coefficient of the function is 0.981, and the determination coefficient is 0.962. The following empirical equation was produced:

$$K_F = 0.2 + 0.9 \cdot P_u \,. \tag{5}$$

The test results have shown that that frost resistance factor depends on closed porosity of concrete. The higher is closed porosity, the higher is frost resistance factor and predicted frost resistance of concrete.

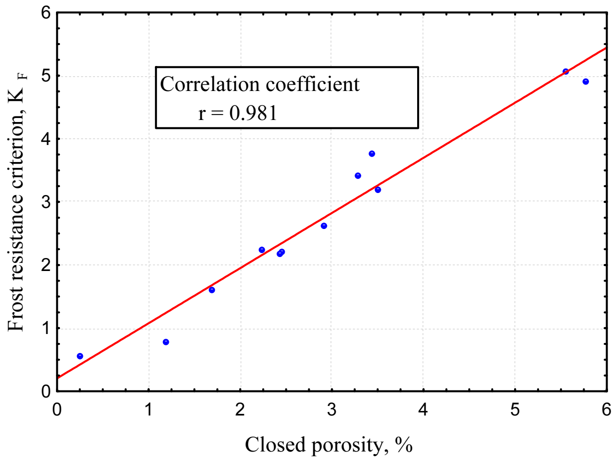

Fig. 9. Function of frost resistance factor and closed porosity

In reference [18] for determination of concrete frost resistance degree C_{Fu} using concrete structure parameters the equation was proposed. It was determinated the main influence on frost resistance degree C_{Fu} has reserve volume *R*, i. e. the closed porosity that is not filled with water, but is gradually fills was freezing-thawing cycles due to water hydraulic pressure. With the increasing closed porosity concrete frost resistance C_{Fu} is increasing. The equation for concrete frost resistance determination is exponential according to authors [18].

The results of aut research show the linear dependence the concrete frost resistance factor K_F dependence on closed porosity. Concrete with high closed porosity has great frost resistance factor K_F. This obtained results are the same like in literature source [18]. But the equation of frost resistance factor K_F from closed porosity is linear, not exponential like in the literature source.

CONCLUSIONS

1. The concrete with bigger course construction has lowest closed porosity and lowest freezing-thawing resistance.
2. With lower coarse aggregate concentration of concrete the average pore size factor λ goes down. Concretes with lower coarse aggregate content have finer pores and better freezing-thawing resistance factor. Pore size uniformity factor α is almost similar in concretes with different coarse aggregate concentration.
3. Statistical processing of test results by using a simple linear function model has produced a function of closed porosity (at the same w/c ratio) and frost resistance factor. The higher is closed porosity, the higher is frost resistance factor and better predicted frost resistance of concrete.

Acknowledgments

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