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CALCULATED PREDICTION OF CONCRETE FROST RESISTANCE

РОЗРАХУНКОВЕ ПРОГНОЗУВАННЯ МОРОЗОСТІЙКОСТІ БЕТОНУ

РАСЧЕТНОЕ ПРОГНОЗИРОВАНИЕ МОРОЗОСТОЙКОСТИ БЕТОНА

Annotation. The equation is experimentally substantiated dependence that relates the value of frost resistance of concrete to the number of cycles of freezing and thawing with an integral structural parameter characterizing the ratio of conditionally closed air pores to the volume of open pores including those filled with ice.

The possibility of calculating the frost resistance of concrete is shown, taking into account its strength and the content of the entrained air, which makes possible to modify well–known algorithms of compositions designing for frost– resistant concrete.

Keywords: frost resistance, capillary porosity, contraction porosity, compensation factor, strength, entrained air volume.

Анотація. У статті наведені експериментальні обґрунтування рівняння, що зв'язує величину морозостійкості бетону за числом допустимих циклів заморожування та відтавання з інтегральним структурним параметром, що характеризує відношення умовно замкнених повітряних пор до об'єму відкритих пор у т.ч. заповнених льодом.

Показана можливість розрахунку морозостійкості бетону з урахуванням його міцності і вмісту втягнутого повітря, що дозволяє модифікувати для морозостійких бетонів відомі алгоритми проектування складів.

Ключові слова: морозостійкість, капілярна пористість, контракцій на пористість, компенсаційний фактор, міцність, об'єм втягнутого повітря.

Аннотация. Экспериментально обосновано уравнение, связывающее величину морозостойкости бетона по числу допустимого числа циклов замораживания и оттаивания с интегральным структурным параметром, характеризующим отношение условно замкнутых воздушных пор к объему открытых пор в т.ч. заполненных льдом.

Показана возможность расчета морозостойкости бетона с учетом его прочности и содержания вовлеченного воздуха, что позволяет совершенствовать для морозостойких бетонов известные алгоритмы проектирования составов.

Ключевые слова: морозостойкость, капиллярная пористость, контракционная пористость, компенсационный фактор, прочность, объем вовле-ченного воздуха.

The urgency of the problem. Most investigations, carried out in order to study the concrete frost resistance problem, were focused on mechanism of concrete destruction under repeatable freezing and thawing and affect of various composition and structure factors on this process [1, 2, 3]. These researches have allowed developing scientific bases for prediction and providing necessary concrete resistance to joint action of water and sign-variable temperatures. They consider the influence of chemical-mineralogical composition of cement and aggregates, their physical-mechanical properties, concrete porous structure features, conditions of concrete compacting and hardening, as well as operating conditions on concrete frost resistance.

At compositions design for frost resistant concrete usually part of these factors is considered at the initial materials choice stage, the others – at selecting the entrained air volume and water cement ratio (W/C). With this aim recommendations, stated in the literature are used [1]. These recommendations are often too generalized and do not give desirable effect. Therefore developing calculated dependencies, relating concrete frost resistance with factors, considered at their compositions design is actual.

Aim of the research. The purpose of the research, whose results are given in this article, is the experimental justification of the calculated dependences of the concrete frost resistance on the parameters of its composition and structure.

Main results of previous studies. The existing dependences of the concrete frost resistance, obtained by different researches are stochastic and are obtained by processing appropriate experimental data. They can be divided into two groups:

1) providing relation between concrete frost resistance and separate factors;

2) providing relation between concrete frost resistance and some more general parameters.

The initial criterion for developing calculated parameters, allowing estimation of frost resistance at compositions proportioning was proposed by Whiteside and Sweet [4]. This criterion is known as «saturation degree» (SD):

$$SD = \frac{V_{f.w}}{V_{f.w} + V_{air}}, \qquad (1)$$

where $V_{f.w}$ and V_{air} are volumes correspondingly of frozen water and air per unit volume of concrete.

Frost resistance (F) is related with saturation degree by a general dependence:

$$F = \frac{1}{SD} = 1 + \frac{V_{air}}{V_{f.w}}. \qquad (2)$$

It was found that at SD < 0.88 concrete has high frost resistance and at SD > 0.91 it collapses rapidly. However, practice shows that neither critical saturation degree value, nor even lower values (SD < 0.88) not unequivocally provide high frost resistance of concrete. It is because at constant SD ratio between the frozen water volume and the total volume of voids in concrete, produced using various compositions, is different.

G. Fagerlund has proposed the following equation for finding the quantity of freezing water (W_f) [5]:

$$W_f = \frac{W/C - 0{,}25\alpha(0{,}73 + K_t)}{W/C + 0{,}32}, \qquad (3)$$

where K_t is a coefficient, considering freezing temperature (for t = -20 °C, K_t = 0.96); α – cement hydration degree, W/C– water–cement ratio.

For a standard temperature (t = -20 °C):

$$W_f = \frac{W/C - 0{,}43\alpha}{W/C + 0{,}32}, \qquad (4)$$

At one of the first attempts to relate the frost resistance with capillary porosity value, for normal hardening concrete, produced using standard cement and aggregates the following dependence was proposed by G. Gorchakov[2]:

$$F = K\,(P_{in.} - P_{cap})^{n}\,, \tag{5}$$

where F is the number of freezing and thawing cycles (causing a certain destruction degree); K, n, P_{in} – parameters, depending on materials quality, concrete composition technological factors; P_{cap} – capillary porosity, %.

Statistical processing of the results the frost resistance tests for normal–weight concrete allowed to specify the dependence of P_{cap} in the form of an empirical equation:

$$F = (14 - P_{cap})^{2.7}\,. \tag{6}$$

Formula (6) can be used considering that the relation between the contraction porosity to the capillary one is at least 0.25 ... 0.3.

Dependence (6) allowed developing a method for finding the concrete composition with required frost resistance [2]. Depending on the required frost resistance value (number of freezing and thawing cycles) and considering the applied cement quality and hardening conditions, the method offers to obtain the necessary capillary porosity value for the designed concrete, selecting using reference data the cement hydration degree and after that to calculate the cement consumption, necessary for obtaining the required capillary porosity. At the same time dependence (6) and developed on its basis compositions proportioning method have a number of drawbacks. The main of them is that the influence of the such structural parameter as ratio between closed pores and opened capillary pores on concrete frost resistance is not considered. It strongly limits application of Eq. (6) only for concrete without artificial air entrainment.

Experimental results and their analysis. Table 1 presents results of calculations, carried out by the author to obtain the concrete frost resistance, depending on water and cement consumptions using for specified materials Eq. (6) and also the real experimental values of frost resistance. Capillary porosity values and relation between the contraction porosity ($P_{con.}$) and capillary one (P_{cap}) are also given.

The value of the capillary porosity was calculated from the formula:

$$P_{cap} = \frac{W - 0{,}5\alpha C}{1000}\,, \tag{7}$$

where W and C – are consumptions of water and cement respectively.

It is very complicated to obtain an exact value of hydrated cement specific volume. According to experimental data [6], obtained at helium adsorption, it varies, depending on cement mineralogy, from 0.411 to 0.386 l/kg. Assuming for calculation that $V_{h.cem} = 1/31 = 0.322$ l/kg, an average value of V_{con} (%) was obtained us [7]. It is in good agreement with experimental values of contraction [8]:

$$V_{con} = 0.06 \cdot \alpha C/10\,. \tag{8}$$

Limitation of $(P_{con.}/P_{cap}) \geq 0.25...0.3$ practically leads to limiting W/C in the range of 0.64...0.7. According to Eq. (6) at W/C < 0.4, the frost resistance significantly grows, reaching 1000 cycles and more. At the same time according to the Portland Cement Association data [9,10] for concrete without artificially entrained air the maximum frost resistance does not exceed 200 cycles. As it follows from Table 1, without entraining air into the concrete mixture the real concrete frost resistance at W/C = 0.4...0.45 can reach 350...400 cycles.

To include the entrained air volume in the frost resistance criterion, some appropriate calculated parameters have been proposed. One of the most known design parameters of this type is «compensation factor» (Fc). It was initially proposed in the following form [1]:

$$F_c = (V_{con} + V_{air})\,/\,V_{ice}\,, \tag{9}$$

where V_{air} is the air volume in compacted concrete mixture, %; V_{con} is the volume of contraction pores in concrete, %; V_{ice} is the volume of water, frozen in concretee at -20 °C.

Eq. (9) reflects a mistakable opinion on a positive role of besides artificially entrained air as well as entrapped air. The entrapped air essentially differs from the air emulsion formed at adding surface-active substances (SAS) because the first is disordered and does not assist to transition the open porosity into closed. The entrapped air bubbles form in concrete voids with a size of up to 0.13 cm (specific sur-

Table 1.

Design and real frost resistance of concrete

Consumption in kg/m³		W/C	P_{cap}, %	$P_{con.}$, %	$P_{con.}/P_{cap}$	F, cycles	
Water	Cement					Calculated according to Eq. (6)	Real
160	200	0.8	8	1.4	0.175	126	63
	250	0.64	6	1.8	0.3	274	110
	300	0.53	4	2.2	0.55	501	220
	400	0.4	0	2.9	-	1243	370
180	200	0.9	10	1.4	0.14	42	40
	281	0.64	6.8	2.0	0.3	206	115
	300	0.6	6	2.2	0.37	274	125
	400	0.45	2	2.9	1.45	820	350
200	200	1	12	1.4	0.117	6	35
	300	0.67	8	2.2	0.275	126	104
	312	0.64	7.5	2.25	0.3	157	105
	400	0.5	4	2.9	0.725	501	220
	500	0.4	0	3.6	-	1243	405

Notes: 1. The cement hydration degree is assumed to be 0.8.

2. The experiments were carried out for concrete on Portland cement without mineral admixtures (28-day strength is 50 MPa, tricalcium aluminate content C_3A = 6 … 8 %), quartz sand with fineness modulus M_f = 2.1 and crushed granite stone 5 ... 20 mm.

3. Frost resistance (freezing-thawing cycles) in Table 1 and in the following is determined accordance to GOST 10060-2012 face less than 760 cm^{-1}). The entrained air bubble, for example using the sodium abietate (Vinsol admixture), varies from 25 to 250 µm (1440 – 2090 cm^{-1}).

Later the following expression was proposed for a compensation factor:

$$F_c = \frac{V_{air.op} + V_{con}}{V_{air} + V_{air.cl}}, \qquad (10)$$

where $V_{air.op}$, $V_{air.cl}$ are correspondingly air in open and closed pores.

For calculating the compensation factor at the concrete composition design it is necessary to find the entrained air volume, the contraction volume of concrete and the volume of created ice. Contraction volume of hardening concrete (%) can be calculated, if absolute volumes of reacting cement and water as well as the absolute volume of hydration products are known:

$$\begin{aligned} V_{con} = [(&\alpha C V_{cem} + 0{,}23\alpha C V_{liq}) - \\ &- (\alpha C + 0{,}23\alpha C)V_{h.cem}]100/1000\,, \end{aligned} \qquad (11)$$

where α is the cement hydration degree; C – cement consumption in kg/m^3; V_{cem} – specific volume of 1 kg of cement; $V_{h.cem}$ – specific volume of hydrated cement; V_{liq} – specific volume of cement paste liquid phase (for concrete without admixtures it is taken to be equal 1).

The volume of frozen water in concrete V_{ice} includes the volume of capillary pores and pores, created due to under compaction of concrete:

$$V_{ice} = \frac{W - 0{,}5\alpha C}{10} + 100\,(1 - K_{comp})\,, \qquad (12)$$

where K_{comp} is the concrete mixture compaction coefficient, obtained as a ratio between the concrete mixture real and calculated densities.

Finally, taking into account the equations (8), (12) the design formula of F_c takes the form:

$$F_c = \frac{10\,V_{air} + 0{,}06\alpha C}{W - 0{,}5\alpha C + 1000\,(1 - K_{comp})}, \qquad (13)$$

For preliminary calculation of porosity parameters the cement hydration degree should be known. Some authors [11] propose to obtain the cement hydration degree (α) using available in the reference literature data, which is unfortunately limited.

For calculating cement hydration degree its relation with cement stone compressive strength, reported by various researchers, may be used. For example, this dependence can be expressed as follows [6]:

$$R_{cem.st} = 238\alpha^3\,, \qquad (14)$$

where $R_{cem.st}$ is the ultimate cement stone compressive strength (MPa).

Cement hydration degree can be also obtained using formulas, relating cement strength R_{cem}, at testing standard cement-sand mortar specimens with relative density *d* [9]:

$$R_{cem} = 110d^2\,, \qquad (15)$$

$$d = \frac{1 + 0{,}23\alpha\rho_{cem}}{1 + \rho_{cem}\,W/C}\,, \qquad (16)$$

where ρ_{cem} is the density of cement.

After statistical processing of experimental data it was found that criterion F_c of concrete frost resistance is described by the following exponential function:

$$F_c = K(10^{F_c} - 1)\,, \qquad (17)$$

where K is a coefficient, depending on the applied cement features.

For Portland cement containing tricalcium aluminate (C_3A) in the range of 6...8%, K = 170. Parameter K can be specified for different materials [7].

Figure 1 shows correspondingly frost resistance values calculated using Eq. (17) and experimental values according to Portland cement Association data [10]. At similar character of dependence F= f(V_{air}), the American data has higher values of F at $V_{air} \geq 2\%$, which can be explained higher values of strength reduction – 25% instead of 5%. Additionally, at F > 700, the calculated estimation of further frost resistance increase is hardly appropriate.

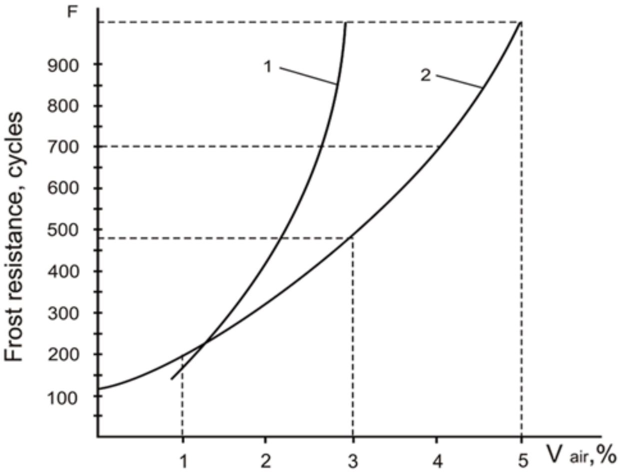

Figure 1. Affect of entrained air on concrete frost resistance:
1 – following the data given in [12]; 2 – according to Eq. (17) at α = 0.7, K = 170, C = 400 kg/m^3, W = 200 l/m^3

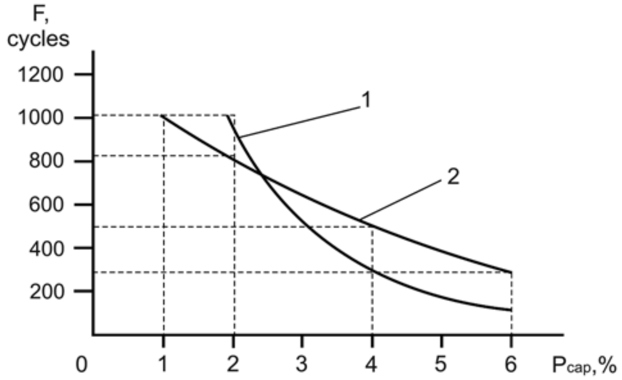

Figure 2. Relationship between capillary porosity and frost resistance:
1 – according to Eq. (17) at α = 0.7, K = 170, C = 400 kg/m^3. Vair = 0 %.
2 – according to formula $F = (14\text{-}P_{cap})^{2.7}$ at α = 0.7, C = 400 kg/m^3 [2].

Formula (17) is valid if high frost resistant crushed granite stone and quartz sand with clay impurity content less 3% are used.

Eq. (17) confirms the experimental dependencies of frost resistance on the capillary porosity value P_{cap}, obtained by many authors (Figure2), as well as relations between the contraction volume, capillary porosity and W/C.

It is evident from Figure 3 that for providing proper concrete frost resistant with and without entrained air, the W/C value should be less than 0.7.

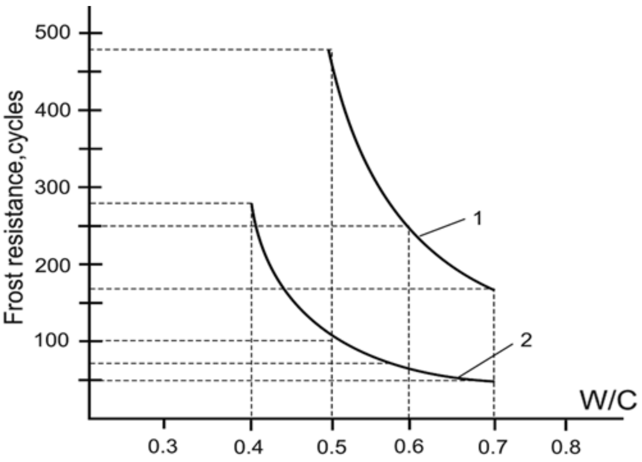

Figure 3. Affect of entrained air on concrete frost resistance (calculations are made according to Eq. (17) at α = 0.6):
1 – V_{air} = 3 %; 2 – V_{air} = 0 %.

For predicting concrete frost resistance and compositions design it is appropriate to use the equations relating the frost resistance, concrete strength and entrained air volume. Unequivocal dependence between concrete strength and strength of cement allows indirect consideration of cement hydration degree, and affect of C/W on concrete strength enables to take into account the concrete density and porosity. The author have carried out concrete frost resistance tests, using impulse ultrasound method at -50 °C and processed the data statistically. The data included 30 series of concrete tests, obtained with using crushed granite stone and quartz sand with fineness modulus $M_f = 1.5…2$. Vinsol resin was used as air entraining admixture.

The processed data array included results of concrete frost resistance measurements in a rather wide compositions diapason ($R_c^{28} = 15…40$ MPa, $W = 140…220$ l/m³, $V_{air} = 0.8…6.5$ %). The data are approximated by a formula that has the following type:

$$F = A_1 R_c^{28^{A_2}} \exp^{A_3 V_{air}}, \qquad (18)$$

where R_c^{28} – compressive strength of concrete in the 28 – day, V_{air} –volume of the entrained air, A_1, A_2, A_3 – coefficients.

For the investigated concrete $A_3 = 0.35$, A_1 and A_2 are varied depending on the water demand and correspondingly mixtures workability (Table 2).

As it follows from analyzing Eq. (18), at entrained air content of 3…5 % the concrete frost resistance increases 3…6 times (Figure 4). For concrete strength above 30…40 MPa the relative increase of critical number of freezing-thawing cycles, achieved by entraining air a little increases. It can be explained by higher influence of closed pores of contraction origin.

Table 2.

Values of coefficients A_1 and A_2 in Eq. (19)
for concrete mixtures with various workability

Concrete mixtures workability	A_1	A_2
Plastic concrete mixtures (Slump Sl = 9…12 cm)	0.34	1.68
Low-plastic concrete mixtures (Slump Sl = 1…4 cm)	0.91	1.47
Non-plastic concrete mixtures	2.48	1.25

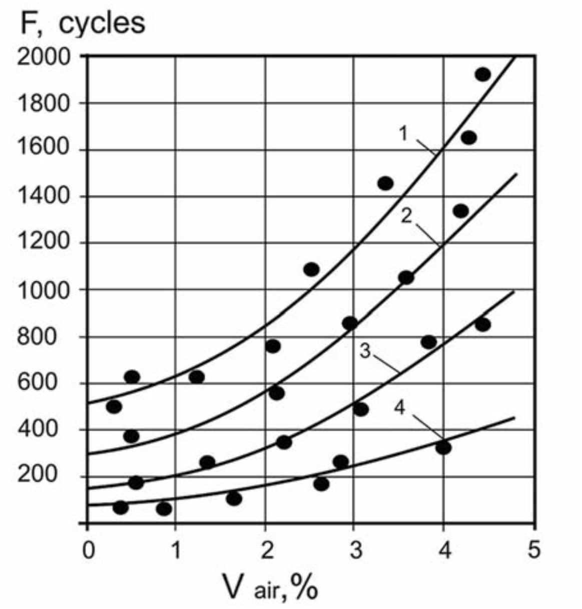

Figure 4. Affect of entrained air on concrete frost resistance (for concrete mixtures with Slump Sl = 1...4 cm) :
1 – R_c^{28} = 70 MPa; 2 – R_c^{28} = 50 MPa;
3 – R_c^{28} = 35 MPa; 4 – R_c^{28} = 20 MPa.

As the empirical data `on the values of parameters A_1 and A_2 is accumulated, Eq. (18) can be widely used either for predicting frost resistance or for concrete compositions design. The algorithm for calculating compositions using Eq. (18) should include checking the possibility of providing the desired number of freezing-thawing cycles at given strength value and, if necessary, corresponding overestimating of R_c^{28} or entraining air [13]. The required entrained air volume in % can be found according to a formula, obtained from Eq. (19):

$$V_{air} = \frac{\ln\left(\dfrac{F}{A_1 R_c^{28^{A_2}}}\right)}{0,35}, \qquad (19)$$

At the same time the necessity of certain overestimating of the initial concrete strength, depending on the entrained air volume, should be considered.

Conclusion.

1. The equation is experimentally substantiated dependence that relates the value of frost resistance of concrete to the number of cycles of freezing and thawing with an integral structural parameter characterizing the ratio of conditionally closed air pores to the volume of open pores including those filled with ice.

2. The possibility of calculating the frost resistance of concrete is shown, taking into account its strength and the content of the entrained air, which makes possible to modify well–known algorithms of compositions designing for frost–resistant concrete.

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