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ESTIMATED FORECASTING OF CONCRETE FROST RESISTANCE IN THE DESIGN OF ITS COMPOSITIONS

РОЗРАХУНКОВЕ ПРОГНОЗУВАННЯ МОРОЗОСТІЙКОСТІ БЕТОНУ ПРИ ПРОЕКТУВАННІ ЙОГО СКЛАДІВ

РАСЧЕТНОЕ ПРОГНОЗИРОВАНИЕ МОРОЗОСТОЙКОСТИ БЕТОНА ПРИ ПРОЕКТИРОВАНИИ ЕГО СОСТАВОВ

Annotation. The article substantiates the possibility of taking into account the required frost resistance of concrete according to the number of cycles of its freezing and thawing in a water-saturated state without significant reduction in strength at the stage of designing its compositions. The review of proposed calculated dependences of frost resistance of concrete on factors of its structure and composition is made, their advantages and disadvantages are analyzed. On the basis of a statistical analysis of the experimental data, a formula is proposed that establishes a relationship between the possible number of cycles of freezing and thawing of concrete with the strength of concrete under compression and the volume of entrained air. An algorithm for designing concrete compositions with a complex of required properties, including frost resistance, and an example of its implementation are given.

Keywords: frost resistance, compressive strength, capillary porosity, entrained air.

Анотація. У статті обґрунтована можливість врахування необхідної морозостійкості бетону за числом циклів його заморожування та відтавання у насиченому водою стані без істотного зниження міцності на стадії проектування його складів. Зроблено огляд запропонованих розрахункових залежностей морозостійкості бетону від факторів його структури та складу, проаналізовано їх переваги та недоліки. На основі статистичного аналізу експериментальних даних запропонована формула, що встановлює зв'язок можливого числа циклів заморожування і відтавання бетону з його міцністю при стиску та об'ємом втягнутого повітря. Наведено алгоритм проектування складів бетону з комплексом необхідних властивостей, включаючи морозостійкість, та приклад його реалізації.

Ключові слова: морозостійкість, міцність при стиску, капілярна пористість, втягнуте повітря.

Аннотация. В статье обоснована возможность учета требуемой морозостойкости бетона по числу циклов его замораживания и оттаивания в насыщенном водой состоянии без существенного снижения прочности на стадии проектирования его составов. Сделан обзор предложенных расчетных зависимостей морозостойкости бетона от факторов его структуры и состава, проанализированы их достоинства и недостатки. На основе статистического анализа экспериментальных данных предложена формула, устанавливающая связь возможного числа циклов замораживания и оттаивания бетона с прочностью бетона при сжатии и объемом вовлеченного воздуха. Приведен алгоритм проектирования составов бетона с комплексом требуемых свойств, включая морозостойкость, и пример его реализации.

Ключевые слова: морозостойкость, прочность при сжатии, капиллярная пористость, вовлеченный воздух.

Introduction

Methodology of concrete compositions design is developed first of all in the direction of taking into account the properties, characterizing concrete durability. Yet D. Abrams has mentioned that «durability and low price» should be considered at concrete compositions design stage along with strength [1].

One of the most important concrete properties, determining its durability, is frost resistance. Concrete frost resistance characterizes its ability to keep the physical-mechanical properties under repeated freezing and thawing in water saturated state. The main concrete frost resistance parameter at laboratory testing is the number of freezing and thawing cycles, which the specimens are able to withstand up to appreciable decrease in strength. Additional parameters for estimating the specimens' destruction degree can be mass losses and reduction of dynamic modulus of elasticity. Standards in various countries offer testing methods that differ by specimens' type, temperature and environment, in which the samples are frozen, duration of each cycle, etc. The number of cycles, obtained in the laboratory, is a conditional parameter, it models the behavior of concrete in real structural elements insufficiently. However, this parameter can be successfully used for comparative frost resistance assessment of concrete with different compositions. American and European standards (ACI 301 and EN 206-1) no include frost resistance requirements to concrete used in structural elements in terms of freezing and thawing cycles, but provide technological recommendations on concrete producing depending on operating conditions. Russian standard (GOST 10060) defined frost resistance classes depending on the number of freezing and thawing cycles the concrete specimens can withstand; the concrete frost resistance class is marked in design documentation on structural elements, considering their operating conditions. Both approaches have advantages and disadvantages and are finally aimed at providing proper durability of structural elements under destructive action of frost and alternating temperatures.

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 [2-5]. These researches have allowed developing scientific bases for prediction and providing necessary concrete resistance to joint action of water and sign-variable temperatures. Obtained recommendations however are often too generalized and do not give desirable effect when proportioning the concrete composition. Therefore developing calculated dependencies, relating concrete frost resistance with factors, considered at their compositions design is actual.

The aim of this work was to obtain the calculated dependence of frost resistance of concrete possible to use in the design of its compositions.

Review of the known calculated dependencies for concrete frost resistance

The existing calculated dependences for forecasting concrete frost resistance are stochastic and are obtained by processing appropriate experimental data.

One of the most important conditions for obtaining frost resistant concrete is providing the required distance between closed pores (distance factor).T. Powers carried out a quantitative analysis of an equation of a distance factor (L) for a hypothetic cement stone model [6] and shown that the concrete frost resistance is provided if:

$$\bar{L} \le L \qquad (1)$$

where $\bar{L}$ is the distance factor value, obtained according to the measurements in the concrete microsections; L is the calculated value of the distance factor.

The distance factor value is determined by specific surface of air voids as well as by the ratio between the cement stone volume in concrete and the air voids volume. It can be calculated according to the following formula:

$$L = \frac{30}{S_{air.v}}[1.4\,(\frac{V_{cem.s}}{V_{air.v}} + 1)^{-1/3} - 1] \qquad (2)$$

where $V_{cem.s}$ is the volume of cement stone in concrete,%; $S_{air.v}$ – specific surface of air voids; $V_{air.v}$ – volume of air voids in concrete,%.

Following Powers, high concrete frost resistance is provided at L ≤ 0.25 mm.

To develop Eq. (2) it was assumed that the system of air voids is idealized and it has the same volume and quantity of air voids, like a real system, but the voids are assumed to be equal and located at equal distancies each related to other.

The distance factor does not consider the essential influence of water-cement ratio (W/C) on frost resistance of concrete with artificially entrained air. For example, according to German standards in order to produce frost resistant concrete with artificially entrained air, both conditions L ≤ 0.25 mm, and W/C ≤ 0.7 should be provided. For frost and sault resistant concrete should be L ≤ 0.20 mm and W/C ≤ 0.6.

A criterion of concrete frost resistance (C_F), considering its open porosity (P_{op}), closed porosity (P_{cl}) and volumetric ice content at given temperature (V_{ice}^{t}) was proposed by G. Dobrolubov[7]:

$$CF = \frac{P_{op} - V_{ice} + P_{cl}}{V_{ice}^{-10°C}} \qquad (3)$$

where $V_{ice}^{-10°C}$ is the volumetric ice content at -10°C.

The parameters in Eq. (3) are obtained experimentally for normal hardened specimens at 28 days. It was shown that the relation between parameter CF and concrete frost resistance is linear [7].

Different experimental methods were proposed for determining the ice content in concrete. The most popular is the calorimetric method, based on the dependence between variation of temperature at water transition to ice and the weight of the formed ice. Ultrasonic and other methods are also used frequently.

For proportioning of concrete with given frost resistance the application of the parameter CF is difficult. For this purpose it is necessary to have reliable enough dependences, allowing passing from the required design parameters of the frost resistance to concrete compositions produced using specific initial materials.

One of the first calculated parameters, allowing estimation of frost resistance at compositions proportioning was proposed by Whiteside and Sweet [8]. This criterion is known as «saturation degree» (SD):

$$SD = \frac{V_{f.w}}{V_{f.w} + V_{air}} \qquad (4)$$

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

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

$$F \sim \frac{1}{SD} = 1 + \frac{V_{air}}{V_{f.w}} \qquad (5)$$

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 its 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.

Initially saturation degree was assumed as experimental parameter, determined by the ratio between the concrete water absorption at atmospheric pressure to its water-saturation under vacuum or at superfluous pressure. The critical water-saturation value is based on the general concept of critical saturation for porose materials at their freezing.

In order to avoid destruction of porous material due to the change of water volume at freezing, the volume of free air voids should be at least 9 %. Many researches have confirmed validity of this concept for concrete. However, Powers has shown that due to entrained air concrete almost always has sufficient free porous volume spaces to resist to the pressure arising due to volume variation at freezing of a porous system saturated by water [9]. At shortage of such internal space the superfluous water should simply leave concrete by moving to the side, where the hydraulic pressure is lower. As when W/C becomes lower and the hydration degree increases the voids' size decreases and less water will freeze at constant temperature.

Substantial part of air voids volume, created without air entraining admixture, does not belong to reserve voids. As a result, for concrete with different compositions, initial materials, hardening conditions and voids' character there is no certain critical water saturation degree. The last is relevant just for concrete with specific compositions. Processing experimental data shows,that depending on composition and structure the critical saturation degree of concrete (SD)cr varies from 0.6 to 0.92 [8].

Calculating the SD value at compositions proportioning stage became possible after developing theoretical concepts on quantity of freezing water in concrete, its porosity and proposing appropriate equations.

G. Fagerlund has proposed the following equation for finding the quantity of freezing water (W_f) [10]:

$$W_f = \frac{W/C - 0.25\alpha(0.73 + K_t)}{W/C + 0.32} \qquad (6)$$

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

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

$$W_f = \frac{W/C - 0.43\alpha}{W/C + 0.32} \qquad (7)$$

Some researchers have shown that at temperatures -20…-30°C the volume of freezing water is close enough to that of capillary pores [11].

There are different design dependencies for finding the capillary porosity of cement stone and concrete, based on various initial preconditions. Formulas for capillary pores volume in 1 m³ of concrete, presented below, differ by numerical coefficients:

O. Kynchevich [12] $$P_{cap} = \frac{W - 0.38\alpha C}{1000} \qquad (8)$$

A. Sheikin [11] $$P_{cap} = \frac{W - 0.42\alpha C}{1000} \qquad (9)$$

G. Gorchakov [13] $$P_{cap} = \frac{W - 0.5\alpha C}{1000} \qquad (10)$$

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

Formula (10) was obtained from the following equation for capillary pores volume in 1 m^3 of concrete:

$$P_{cap} = (W - W_{gel}\alpha C - q_{con}\alpha C) / 1000 \qquad (11)$$

where $q_{con}\alpha C$ is the contraction volume; W_{gel} – quantity of water, binded by the cement gel ($W = 0.38…0.42$); q_{con} – contraction coefficient ($q_{con} = 0.09…0.15$).

If the contraction volume is not considered, as follows from Eq. (11), formula (10) is practically identical to (8…9).

A. Sheikin [11] has assumed for developing Eq. (9) that the density of chemically bound water is 1. Considering that the water density in crystalline hydrates is higher than 1, the numerical coefficient before α can be lower than 0.42.

Depending on mineralogical cement composition and its hardening conditions, the value of the coefficient before α can differs from that given in Eqs. (8…10) [9].

It was also experimentally proved that the increase of the ratio between contraction volume and capillary porosity is an essential factor for increasing the frost resistance [12, 13]. The contraction volume can be determined as a part of capillary volume, created due to decreasing the volume of hydrate compounds at the time of cement hardening compared with the volumes of cement and water participating in the reactions of hydration. For cement stone, hardened without water absorption and evaporation the contraction volume is 0.05…0.04 at W/C = 0.4…0.6 for hydration degree 0.02…0.016 [12].Considering the positive influence of contraction volume, for finding the saturation degree SD it is expediently to use formula (10) for calculating the capillary porosity.

As one of the first attempts to relate the frost resistance with capillary porosity value, for normal hardening concrete, produced using standard materials, the following dependence was proposed by G. Gorchakov[13]:

$$F = (14 - P_{cap})^{2.7} \qquad (12)$$

where F is the number of freezing cycles (causing a certain destruction degree); P_{cap} – capillary porosity, %.

For finding P_{cap} formula (10) can be used considering that the relation between the contraction porosity to the capillary one is at least 0.25…0.3. The dependence (12) allowed developing a method for finding the concrete composition with required frost resistance [13]. Depending on the required frost resistance value (number of freezing and thawing cycles), considering the applied cement quality and hardening conditions, this method offers to find the capillary porosity value for the designed concrete, selecting 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 the found cement consumption should not be lower than that, obtained from the strength condition. Having allowed, unlike a method of forecasting frost resistance by saturation degree, to pass from quality estimations to quantitative, at the same time dependence (12) 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 limits application of Eq. (12) only for concrete without artificial air entrainment.

Table 1 presents results of calculations, carried out by the author to obtain the value of concrete frost resistance, depending on water and cement consumptions using the adjusted for specified materials Eq. (12) and Eq (10) and the real experimental values of frost resistance.

According to Eq. (12) 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 [14] 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.

A. Sheikin [15] has proposed a frost resistance criterion (KF), based on a hypothesis that the closed porosity of concrete (P_{cl}) for preventing its destruction by freezing and thawing should be at least like the possible growth of water volume that fills the concrete pores space at its freezing:

$$K_F = \frac{P_{cl}}{0.09P_{op}} \geq 1 \qquad (13)$$

where P_{op} – open porosity, equal to the volumetric water saturation of concrete.

Table 1.

Design and real frost resistance of concrete

Consumption in kg/m³		W/C	Pcap, %	F, cycles	
Water	Cement			Calculated according to Eq. (12)	Real
160	200	0.8	8	126	63
	250	0.64	6	274	110
	300	0.53	4	501	220
	400	0.4	0	1243	370
180	200	0.9	10	42	40
	281	0.64	6.8	206	115
	300	0.6	6	274	125
	400	0.45	2	820	350
200	200	1	12	6	35
	300	0.67	8	126	104
	312	0.64	7.5	157	105
	400	0.5	4	501	220
	500	0.4	0	1243	405

In essence, this criterion is based on the same concept like saturation degree SD. The closed porosity in criterion K_F is proposed to be considered just as contraction volume of the hardening cement stone.

The open concrete porosity (P_{op}) is calculated as a difference between the total porosity (P_t) and contraction volume (P_{con}), i.e. in essence it equals to the sum of capillary and cement gel porosity [11]:

$$P_{op} = P_t - P_{con} = (W - 0.23\alpha C) - 0.041\alpha C = W - 0.271\alpha C \qquad (14)$$

The assumption regarding negative influence of cement gel porosity along with the capillary one on concrete frost resistance is not proved. As known, water in gel pores is in a special state and does not transfer to ice at low temperatures about -40°C, and even -78°C [9].

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 (F_c)»[3]:

$$F_c = \frac{V_{air.cl} + V_{con}}{V_{ice} + V_{air.op}} \qquad (15)$$

where $V_{air.op}$,$V_{air.cl}$ are correspondingly air in open and closed pores, V_{con} – is the volume contraction volume, V_{ice} – is the volume of water, frozen in concrete at -20°C.

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. The value of V_{con} according to various data varies from 0.041 up to 0.09αC/10 [11].

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

$$V_{ice} = \frac{W - 0.5\alpha C}{10} + 100(1 - K_{comp}) \qquad (16)$$

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 porosity equation (16) and $V_{con} \approx 0.6\alpha C/10$ the design formula of F_c takes the form:

$$F_c = \frac{10V_{air.cl} + 0.6\alpha C}{W - 0.5\alpha C + 1000(1 - K_{comp})} \qquad (17)$$

Approximately cement hydration degree can be calculated using formulas, relating the cement strength R_{cem}, at testing standard cement-sand mortar specimens with relative density d [11]:

$$R_{cem} = 110d^2, \tag{18}$$

$$d = \left(\frac{1 + 0.23\alpha\rho_{cem}}{W - 0.5\alpha C + 1000(1 - K_{comp})}\right) \tag{19}$$

where ρ_{cem} is the density of cement.

However, the above mentioned dependencies do not allow estimation of cement hydration degree in concrete considering the applied cement features as well as the concrete mixture W/C.

After statistical processing of experimental data it was found that criterion F_c of concrete frost resistance is described by the following exponential function [5]:

$$F = K(10^{Fc} - 1) \tag{20}$$

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 must be specified for different materials [5].

Formula (20) is valid if high frost resistant crushed granite stone and quartz sand with clay impurity content less 3% are used.

Figure 1 shows correspondingly frost resistance values calculated using Eq. (20) and experimental values according to Portland cement Association data [14]. At similar character of dependence $F = f(V_{air})$, the American data (curve 1) has higher values of F at $V_{air} \geq 2\%$, which can be explained higher allowable of strength reduction – 25% instead of 5%(curve 2). Additionally, at F > 700, the calculated estimation of further frost resistance is hardly appropriate.

Eq. (20) confirms the experimental dependencies of frost resistance on the capillary porosity value Pcap, obtained by many authors (Figure 2).

It is evident also from Figure 3,obtained by calculations with help Eq (20),at α = 0.6 that for providing proper concrete frost resistant with and without entrained air, the W/C value should be less than 0.7.

Approximateness of calculated cement hydration degree and reserved porosity decrease the predicted importance of compensation factor as frost resistance criteria. 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.

Materials and methods

To determine the calculated dependence of the frost resistance of concrete on its compressive strength and the volume of entrained air, 30 series of concrete samples of various compositions were tested. Samples were made using Portland cement of the second type CEM II/A-S according to EN 197-1: 2000 on the basis of clinker with mineralogical composition: $3CaO{\cdot}SiO_2$ – 59…63 %, $2CaO{\cdot}SiO_2$ – 12…15 %, $3CaO{\cdot}Al_2O_3$ – 6…8 %, C_4AF – 15…23 %. The cement included of blast-furnace granulated slag in an amount of 20%. The strength of Portland cement corresponded to the class 42.5 N.

A fine aggregate of concrete was quartz sand with a modulus of fineness M_f = 1.5…2 and a content of dust and clay impurities of 1…3%, granite crush stone of the fraction 5…20 mm being a large aggregate. In concrete mixtures, Vinsol resin was added as an air-entraining admixture in the amount of 0.01…0.03% of the mass of the cement.

Depending on the content of the mixing water, the workability of concrete mixtures varied in a wide range characteristic of plastic and stiff mixtures.

The volume of entrained air was determined by the compression method, based on the Boyle-Mariotte law, establishing the relationship between the air volume and the applied pressure at a constant temperature.

The samples of concrete were compacted by vibrating on a laboratory vibroplatform to a compacting coefficient of Kcomp not less than 0.98. After hardening the samples under normal conditions for 28 days, they were tested for compressive strength, and also for frost resistance.

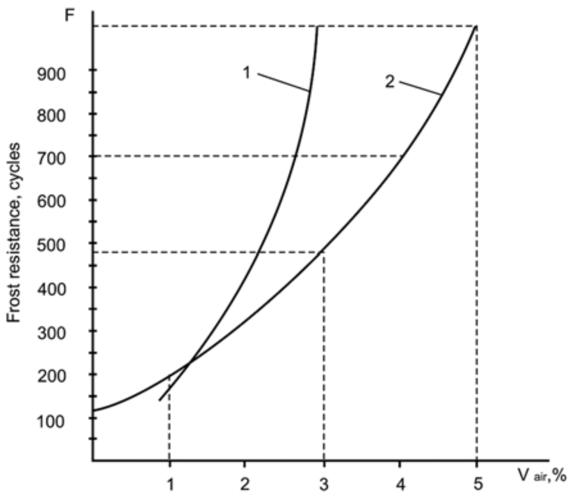

Figure 1. Affect of entrained air on concrete frost resistance:
1 – following the data given in [14];
2 – at α = 0.7, K = 170, C = 400 kg/m^3, W = 200 l/m^3.

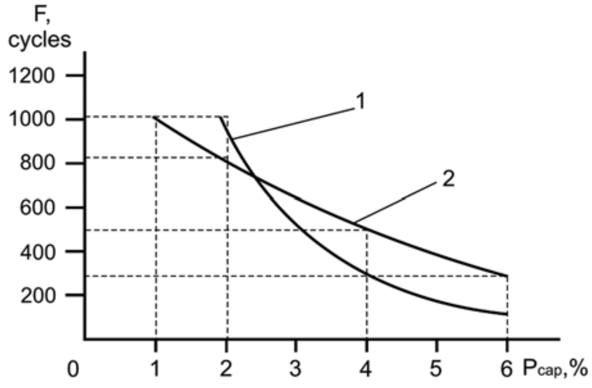

Figure 2. Relationship between capillary porosity and frost resistance:
1 –according to Eq. (20) at α = 0.7, K = 170, C = 400 kg/m^3. V_{air} = 0 %.
2 – according to formula (12) at α = 0.7, C = 400 kg/m^3 [13].

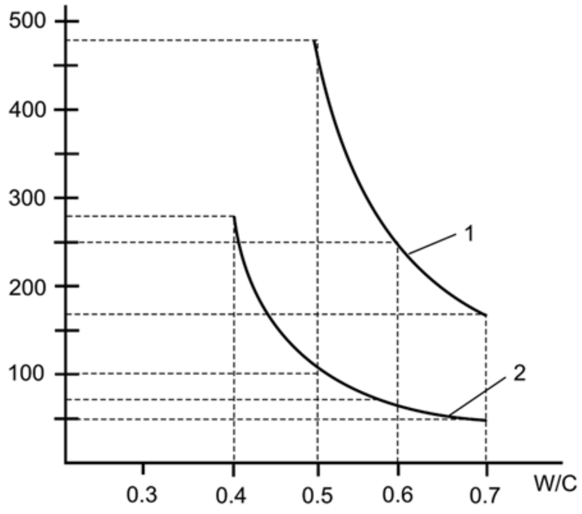

Figure 3. Affect of entrained air on concrete frost resistance:
1 – V_{air} = 3 %; 2 – V_{air} = 0 %.

The frost resistance of concrete was determined by an ultrasonic method based on determining the propagation time of ultrasound in the samples during their alternating freezing and thawing. The concrete frost resistance grade was established by the critical number of freezing and thawing cycles, from which a sharp increase in the ultrasonic propagation time in the sample occurs, which corresponds to the onset of its intensive destruction. For this purpose, the corresponding coefficients linking the critical number of cycles and the concrete grade for frost resistance availiable in the standard for ultrasonic method (GOST 26134-80) were used. This method allowsed carrying out the experiments within a relatively short time at minimum number of samples and with low expenditure.

Experimental results and their application

The tests performed results for strength and frost resistance of concrete samples different compositions are given in Table 2. As it follows from Table 2, the processed data array includes results of concrete frost resistance measurements in a rather wide compositions range and accordingly concrete strength ($R_c^{28} = 15 \ldots 40$ MPa, $W = 140 \ldots 220$ l/m^3, $V_{air} = 0.8 \ldots 6.5$ %). The data are approximised by a formula that has the following type:

$$F = A_1 R_c^{28\,A_2} \exp^{A_3 V_{air}} \qquad (21)$$

Table 2.

Results of concrete frost resistance testing, used for statistical processing

№	Water demand of the concrete mixture W, l/m^3	Concrete strength at 28 days R_c^{28}, MPa	Entrained air volume V_{air}, %	Real frost resistance of concrete Fr, cycles	Calculated frost resistance of concrete F_c, cycles	Deviation, (F_r-F_c)	(F_r-F_c) 100%/ Fr
1	220	15.3	1.2	32	46	14	30
2	200	15.1	2.1	84	65	19	30
3	190	15.2	3.1	119	92	28	30
4	200	20.4	1.3	55	74	18	25
5	190	20.2	2.2	131	105	26	25
6	190	20.2	3.2	112	149	37	25
7	180	20.5	3.5	133	178	44	25
8	180	20.1	4.2	169	211	42	20
9	175	20.3	4.5	449	359	90	25
10	190	25.2	2.5	218	192	36	20
11	180	25.1	3.5	220	258	39	15
12	180	25.2	4.1	369	308	62	20
13	170	25.3	5.5	713	594	119	20
14	190	30.2	1.2	124	146	22	15
15	190	30.1	2.1	239	208	31	15
16	180	30.2	3.2	250	294	44	15
17	180	30.4	4.3	355	418	63	15
18	170	30.5	5.1	822	777	155	20
19	170	30.3	5.5	1111	926	185	20
20	160	30.2	6.1	1323	1103	221	20
21	160	30.3	6.5	985	1313	328	25
22	180	35.2	2.3	336	269	67	25
23	170	35.1	3.2	411	484	73	15
24	170	35.3	4.1	790	687	103	15
25	160	35.4	5.2	1121	975	146	15
26	150	35.2	6.1	2069	1724	345	20
27	170	40.2	3.3	501	589	88	15
28	160	40.3	4.2	710	836	125	15
29	150	40.5	5.1	1651	1436	215	15
30	150	40.5	6.1	1630	2037	407	20
31	140	40.2	6.5	2912	2427	485	20

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 3).

As it follows from analyzing Eq. (21), 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 begin to gecrease.

As the empirical data on the values of parameters A_1 and A_2 is accumulated, Eq. (21) can be widely used either for predicting frost resistance or for concrete compositions design. The algorithm for calculating compositions using Eq. (21) should include checking the possibility of providing the desired number of freezing-thawing cycles at given strength value and, if necessary, corresponding overestimating of concrete compressive strength in 28 days (R_c^{28}) or volume of entraining air. The required entrained air volume in % can be found according to a formula, obtained from Eq. (21):

$$V_{air} = \frac{\ln\left(\frac{F}{A_1 R_c^{28 A_2}}\right)}{0.35} \qquad (22)$$

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

Algorithms for designing concrete compositions (Table 4) suggest finding the basic parameters of the mixture – cement-water ratio (C/W), water consumption (W), entrained air volume (V_{air}) and consumptions of other concrete mixture components, providing the complex of given properties in the most effective manner.

When solving the problems of designing compositions of frost – resistant concrete in combination with formulas (21) and (22) other design dependencies and reference recommendations can be used to determine the optimal consumptions of all components of the concrete mixture that provide the required properties of concrete [2,3]

Table 3.

Values of coefficients A_1 and A_2 in Eq. (21) for concrete mixtures with various workability

Concrete mixtures workability	**A1**	**A2**
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

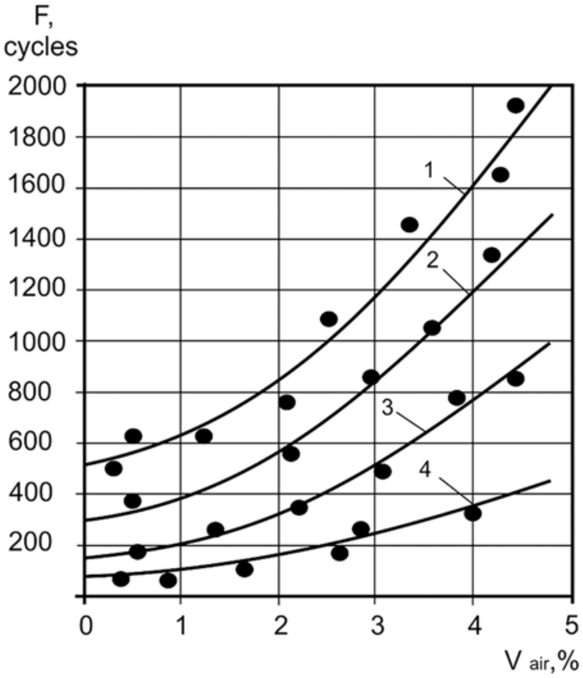

Figure 4. Affect of entrained air on concrete frost resistance (for concrete mixtures with Slump Sl= 1…4 cm):
1 – R_c^{28} = 70 MPa; 2 – R_c^{28} = 50 MPa;
3 – R_c^{28} = 35 MPa; 4 – R_c^{28} = 20 MPa.

Table 4.

Scheme of the algorithm for designing the concrete composition with the required frost resistance

1. Determine the required average strength level (R_1) of concrete, providing a given class of concrete for compressive strength.
2. Determine the compressive strength of concrete (R_2), which provides the values of other normalized properties of concrete.
3. For further calculation choose by comparison R_1 and R_2 a higher value of the compressive strength of concrete.
4. By the formula (22) determine the volume of the air (emulsified by means of the air-entraining additive), which ensures V_{air1} at a given strength, the required class for frost resistance,%.
5. Clarify the required strength of the concrete taking into account the effect of the air involved, assuming that the introduction of 1% of the entrained air into the concrete mixture reduces the compressive strength of the concrete by an average of 5 %.
6. Clarify the volume of entrained air V_{air2}, providing the required frost resistance at the design strength of concrete.
7. Calculate the W/C of the concrete mixture, which provides the given concrete compressive strength.
8. Find the water content taking into account the workability of the concrete mixture and the characteristics of the aggregates.
9. Determine the consumption of cement and other components of the concrete mixture.

Example

Calculate the composition of concrete for a single-layer coating of a road with specified compressive $R_c = 30$ MPa and bending strength $R_{tв} = 4.4$ MPa. Concrete class for frost resistance F300. The concrete mixture is stacked in the coating with Sl = 2 cm.

Initial materials: portland cement with compressive strength in 28 days (R_{cem}) – 50 MPa and normal consistency 25.5%; quartz sand with a modulus of fineness $M_f = 2.2$, content of dust impurities 2.5%, density $\rho_s = 2.67$ kg/l, bulk density. $\rho_{b.s.} = 1.55$ kg/l; granite crushed stone of fraction 5-40 mm, $\rho_{c.s} = 2.7$ kg/l, $\rho_{B.c.s} = 1.4$ kg/l, the content of dust impurities is 0.8 %. An air-entraining additive is introduced.

For the calculation, use the algorithm given in Table. 4

1. Determine by the formula ($R_{tв} = 0.08(10R)^{2/3}$)[3] the necessary compressive strength (R_{c1}), which ensures the normalized bending strength:

$$R_{c1} = 40.8 \text{ MPa}$$

2. Since $R_{c1} > R_c$ is taken for further calculations ($R_c = 40.8$ MPa)

3. Using formula (22), determine the required volume of entrained air, which, at the given strength, provides the required class for frost resistance. The coefficients A_1 and A_2 are chosen according to table 3 taking into account the fluidity of the concrete mixture (Sl = 2 cm):

$$V_{air} = \frac{\ln\left(\frac{300}{0.91 \cdot 40.8^{1.47}}\right)}{0.35} \approx 1.0\ \%$$

4. Specify concrete strength values taking into account the influence of the entrained air:

$$R'_{c1} = 40.8 - 0.05 \cdot 1 \cdot 40.8 = 38.8 \text{ MPa}$$

5. Necessary compressive strength of concrete, which provides the given strength values for bending and frost resistance, taking into account the entrained air:

$$R''_{c1} = 40.8\,\frac{40.8}{38.8} \approx 43 \text{ MPa}$$

6. Calculate the W/C of the concrete mixture, which provides the design compressive strength of concrete. For the calculation use well – known [3] formula

$$R_c = AR_{cem}(C/W - 0.5)$$

where A – the coefficient of the quality of the used materials. Accepted A = 0.55:

$$W/C = \frac{AR_{cem}}{R + 0.5AR_{cem}} = \frac{0.55 \cdot 50}{43 + 0.5 \cdot 0.55 \cdot 50} = 0.49$$

7. The water content for the given fluidity of the concrete mixture, taking into account the characteristics of the aggregates, will be 180 l/m³ [3].

8. Cement consumption:

$$C = \frac{W}{W/C} = \frac{180}{0.49} = 368 \text{ kg/m}^3$$

9. Consumption of crush stone obtain by the formula, obtained by solving a system of two equations.

$$\begin{cases} \dfrac{C}{\rho_c} + \dfrac{W}{\rho_w} + \dfrac{S}{\rho_s} + \dfrac{C.S}{\rho_{c.s}} = 1000 \\ \dfrac{C}{\rho_c} + \dfrac{W}{\rho_w} + \dfrac{S}{\rho_s} = \alpha P_{c.s}\,\dfrac{C.S}{\rho_{B.c.s}} \end{cases}$$

Where C, W, S, C.S – accordingly consumption of cement, water, sand and crush stone, and ρ_c, ρ_w, ρ_s, $\rho_{c.s}$ – their densities; $\rho_{B.c.s}$ – bulk density of crush stone and $P_{c.s}$ – its vacuity ($P_{c.s} = 0.48$); α – coefficient of filling of voids and expansion crush stone grains in concrete mixture by cement – sand mortar (α = 1.39) [3].

$$C.S = \frac{1000}{\dfrac{1}{\rho_{c.s}} = \dfrac{\alpha P_{c.s}}{\rho_{B.c.s}}}$$

$$C.S. = \frac{1000}{\dfrac{1}{2.7} + 1.39 \cdot 0.48\,\dfrac{1}{1.4}} = 1181 \text{ kg/m}^3$$

10. We will find the sand consumption in view of the involved air [2]:

$$S = (1000 - V_c - V_{c.s} - V_w - V_{air})$$

where V_c, $V_{c.s}$, V_w, V_{air} – accordingly volumes of cement, crush stone, water and air.

$$S = \left(1000 - \frac{368}{3.1} - \frac{1181}{2.7} - 180 - 10\right) 2.67 = 680 \text{ kg/m}^3$$

Calculated composition of concrete:

$C = 368$ kg/m³; $W = 180$ kg/m³;

$C.S = 1181$ kg/m³; $S = 680$ kg/m³; $V_{air} = 10$ l/m³.

Conclusion

The processing of experimental data allowed us to find the calculated dependences establishing the relationship between frost resistance, strength of concrete and the content of the entrained air. These calculated dependences can be used to solve of designing concrete compositions problems with a frost resistance value by the permissible number of cycles of its freezing and thawing.

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