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Method of calculating the optimal sand content in normal-weight concrete

Метод расчета оптимального содержания песка в тяжелом бетоне

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Ключевые слова: бетонная смесь; оптимальное содержание песка; вязкость; водопотребность; водоотделение; объем вовлеченного воздуха; расчет

Abstract. In the practice of proportioning concrete compositions, the optimum sand content in a mixture of aggregates is usually found empirically. The disadvantage of this approach is the considerable complexity and duration of the required tests. The aim of the work is to develop a calculation methodology for finding the content of sand in the normal-weight concrete, taking into account the optimality criteria given. Based on the well-known theoretical concepts, the design equations are substantiated for finding the content of sand in a mixture of concrete aggregates, which ensures the lowest viscosity of the concrete mixture and prevent water separation. Using the experimental-statistical model, a method is also proposed for finding the sand content in concrete that provides the required volume of entrained air. The proposed calculation methods are confirmed experimentally.

Аннотация. В практике подбора составов бетона оптимальное содержание песка в смеси заполнителей находят обычно эмпирически. Недостатком такого подхода является значительная трудоемкость и продолжительность необходимых испытаний. Целью работы является разработка расчетной методики определения содержания песка в тяжелом бетоне с учетом заданных критериев оптимальности. На основе известных теоретических представлений обосновываются расчетные уравнения для нахождения содержания песка в смеси заполнителей бетона, обеспечивающего наименьшую вязкость бетонной смеси и предотвращение водоотделения. С помощью экспериментально-статистической модели предлагается также метод нахождения содержания песка в бетоне, обеспечивающего требуемый объем вовлеченного воздуха. Предлагаемые расчетные методики подтверждаются экспериментально.

1. Introduction

One of the primary goals of concrete composition optimization is obtaining the aggregates ratio, providing the minimal cement consumption at normalized concrete properties. Selection of fine and coarse aggregates ratio in concrete based on taking into account its influence on the properties of the concrete mixture and concrete on the one hand and cement consumption on the other. In concrete proportioning practice empirical recommendations are usually used for finding a portion of sand in a mixture of aggregates (r) or unequivocally related to this portion coefficient K_s, considering moving apart of a coarse aggregate grains by cement – sand mortar.

One of the first attempts to receive an analytical dependence for finding the grading of aggregates in view of concrete mixtures workability was made by Bolomey [1]. Unlike other known dependencies, proposed for finding the grading of dry mixtures with maximum density, characterizing the so-called 'ideal' sifting curves [1–3], Bolomey proposed to divide concrete mixtures into two types – stiff (semi-dry or dry) and plastic by applying a special coefficient in the formula he offered.

A general form of Bolomey's formula is given below:

$$y = A + (100 - A)\sqrt{\frac{d}{D}}, \qquad (1)$$

where y – the content of aggregates passing through a sieve, %; d – the diameter of sieve openings, mm; D – ultimate aggregates grains size, mm; A – a coefficient that at the use of gravel and sand equals 8 and 10 for stiff and plastic concrete mixtures correspondingly, and at the use of crushed stone and sand – 10 and 12, respectively.

Later equations for design of concrete mixtures grains size distribution with a more narrow workability gradation were proposed [4–6]. However empirical dependences of this type are excessively general, do not consider the cement paste consumption and specific materials features [7–13].

Further attempts to calculate the optimum sand content in concrete mixtures were made at different time and based on various theoretical preconditions [14–16].

The optimum sand content rule can be considered as consequence of concrete mixtures water demand constancy rule. The water demand constancy rule (WDCR) has been found in the beginning of 30$^{\underline{th}}$ of the last century by Soroker in the USSR and McMillan in the USA [1–3]. It was reported that at constant water content cement consumption within the limits of 200…400 kg/m^3 does not essentially affect the concrete mixtures workability. Initially WDCR was applied only to low-slump mixtures. Later it was experimentally confirmed for no-slump and high-slump concrete mixtures.

Based on WDCR, graphs and tables for rough estimation of concrete mixtures water content, depending on cone slump and Vebe time were proposed [1, 17, 18]. Empirical recommendations for finding the concrete mixtures water content considering WDCR are presently used in normal weight concrete proportioning methods, recommended in many countries.

Essential stabilization of the upper limit of WDCR area and considering the features of cements, is achieved by expressing it by critical water-cement ratio ($(W/C)_{cr}$), equal to 1.68 N.C (average), where N.C, is a W/C, corresponding to the cement paste normal consistency [19, 20].

The water demand constancy rule proceed from a simplified picture of concrete mixture rheological properties changes depending on W/C. It was shown [1, 20] that the logarithm of concrete mixture viscosity changes linearly practically in the entire W/C range. However, if W/C varies from 0.8 to 0.5, viscosity changes from 10 to 100 poises, than at W/C change from 0.5 to 0.2 viscosity increases from 100 to 10000 poises i.e. an order above.

Different equations were proposed for dispersion systems viscosity (ηsm). These equations are modifications of Einstein's formula [1].

Powers has proposed an exponential equation for concrete mixtures viscosity [21]:

$$\eta / \eta_0 = e^{K\varphi}, \qquad (2)$$

where η and η_0 are viscosity of mixture and initial dispersion medium; K is a coefficient; φ is the dispersion phase volumetric concentration.

Experimental data [1] allow presenting Eg (2) as:

$$\eta_{c.m} = K_o e^{\eta_{cem.p.}\varphi_{agg}}, \qquad (3)$$

where $\eta_{c.m}$ – viscosity of concrete mixture, $\eta_{cem.p}$ – cement paste viscosity, K_O – proportionality coefficient ($K_O \approx 20$), φ_{agg} – aggregate volumetric concentration.

In turn the cement paste viscosity:

$$\eta_{cem.p.} = be^{a\varphi_{cem}}, \qquad (4)$$

where a and b – average empirical coefficients (a = 19, b = 5.3·10^{-4}); φ_{cem} – volumetric concentration of cement in the cement paste.

The volumetric concentration of cement in the cement paste is unequivocally characterized by the cement – water ratio (V_{cem}/V_w):

$$\varphi_{cem} = \frac{V_{cem}/V_w}{1+V_{cem}/V_w}. \quad (5)$$

where V_{cem} is the volume of cement, V_w is the water volume.

The aggregate volumetric concentration:

$$\varphi_{agg} = \frac{K_1 - 1}{K_1 + \delta K_2}, \quad (6)$$

where δ – average thickness of the cement paste film; $K_1 = \left(P_{agg}+1\right)/P_{agg}$ is a coefficient, considering the aggregates voidage; $K_2 = U_{agg}/P_{agg}$ is a coefficient, considering complexly the aggregates voidage and specific surface.

Taking into account the above mentioned expressions, the equation for concrete mixture viscosity (3) takes the following form [1]:

$$\eta_{c.m} = K_o \exp\left(\frac{b(K_1-1)}{K_1+\delta K_2} \exp\frac{a(V_{cem}/V_w)}{1+V_{cem}/V_w}\right) \quad (7)$$

As shown by a number of researchers, the sand content in the mixture of aggregates affects not only on its water content but water-holding and air-entraining ability [1, 22] also, which is important to consider when designing concrete compositions.

In our study, the results of which are presented this article proposes the calculated dependencies that allow to select the optimal sand content in the design determination of the composition of the concrete mixture with the subsequent experimental refinement.

The aim of the work was to theoretically substantiate and develop a method for calculating the optimal sand content in a mixture of aggregates of concrete mixtures (r_0). Three characteristic options for optimization of the conditions are considered:

minimizing viscosity ($\eta_{c.m}$) or water content (W) of concrete mixture:

$$r \to r_{opt} \text{ at } \eta_{c.m} \to min \ (W \to min)$$

1. minimization of water separation (W_s) concrete mixture:

$$r \to r'_{opt} \text{ at } W_s \to min$$

2. ensure the required content of entrained air (A^r)

$$r \to r''_{opt} \text{ at } A^0 \to A^r$$

To achieve this goal it was necessary to justify:

– the design equation for the viscosity of a concrete mixture, taking into account the impact of a certain cement-water ratio of aggregates with regard to their voidness and specific surface, as well as the volume of cement paste;

– the equation that allows to determine the amount of water kept in the concrete mixture, taking into account the content and water demand of cement, the water demand and the ratio of aggregates;

– the equation that allows to calculate the volume of entrained air for concrete mixtures of different workability depending on the main factors characterizing their composition.

2. Methods and materials

The experiments were carried out using a typical mid-aluminate Portland cement that does not contain mineral additives.

Quartz sands with a modulus of fineness M_f = 1.7 and M_f = 2.4 and a water demand of respectively 7 and 9.5 % were used as fine aggregate of concrete.

The water demand of sand (W_s) was found by the method [23], which consists in determining the amount of water in% of the mass of sand, which must be added to the mortar mixture of 1:2, so that its mobility on the shaking table was identical the mobility of the cement paste of normal consistency.

$$W_s = \frac{(W/C)_m - (W/C)_{c.p}}{2} \cdot 100\%, \quad (8)$$

where $(W/C)_m$ – the water-cement ratio of the mortar mixture with the spreading of the cone equal to the spreading of the cement paste; $(W/C)_{c.p}$ – (W/C) of the normal consistency cement paste.

Granite crushed stone of fraction 5...20 mm was used as a coarse aggregate.

Determination of the properties of the concrete mixture was performed in accordance with EN 206-1: 2000. Water separation (W_s) was characterized by the volume of water separated from the concrete mixture after 1.5 h, to its volume by the formula:

$$W_s = \frac{m_{w.s}}{\rho_w V_{c.m}}, \quad (9)$$

where $m_{w.s}$ – the mass of separated water, g; ρ_w – the density of water (ρ_w = g/cm^3); $V_{c.m}$ – is the volume of compacted concrete mixture, cm^3.

For a certain volume of entrained air, a compression method based on the Boyle-Mariotte law was used, which establishes the relationship between the air volume and the applied pressure.

For receiving a polynomial model of the entrained air volume experiments were carried out according to factorial plan Ha_5 [14]. As initial materials for a concrete mixture were Portland cement (28 day compressive strength is 50 MPa) without mineral admixtures, crushed granite stone 5…20 mm, quartz sand (clay, silt and dust content is 0.8 %). The sand was divided into two fractions: 0.63...2.5 mm and less than 0.63 mm which were mixed in a required proportion. Air-entrained admixture was used.

3. Results and Discussion

As it follows from Eq. (7), viscosity and consequently workability of concrete mixtures with constant initial materials is defined in a common case by the cement paste cement-water ratio and by the thickness of the cement paste film (δ) on the aggregates grains.

Calculating δ is possible at known values of cement paste volume ($V_{c.p}$), aggregates voidage (P_{agg}) relative to their absolute volume (P_{agg}) and coarse and fine aggregates' total specific surface (U_{agg} V_{agg}):

$$\delta = \frac{V_{c.p} - P_{agg}(1 - V_{c.p})}{U_{agg} V_{agg}}, \quad (10)$$

where U_{agg} – the specific surface of the aggregates mixture, m^2/m^3; V_{agg} – the volume of the aggregates mixture, m^3.

The aggregates' surface monotonically increases with sand content growth and can be calculated at known values of fine and coarse aggregates specific surfaces (U_s) and ($U_{cr.s}$) using the condition:

$$U_{agg} V_{agg} = U_s r + U_{cr.s}(1 - r) = U_{cr.s} + (U_s - U_{cr.s}) r\,. \quad (11)$$

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It is practically impossible to carry out an exact theoretical calculation of aggregates' voidage depending on their volumetric ratio, because the integral value P_{agg} of aggregates' mixture depends on their location in a space, which is in turn defined by form, grains' surface features, etc. Rough calculation of fine and coarse aggregates dry mixture's voidage is possible by assuming a parabolic type approximating curve (Figure 1) and writing equations for its three points:

$$\begin{cases} P_{cr.s} = ar_1^2 + br_1 + c \\ P_s = ar_2^2 + br_2 + c \\ P_x = ar_x^2 + br_x + c \end{cases}, \quad (12)$$

where $P_{cr.s}$, P_s are the values of voidage (by absolute volume) of coarse and fine aggregates, accordingly in compacted (by vibrating) condition; r_1 and r_2- are the border values of r on the curve (Figure 1); $P_{a.x}$ is the experimental value of aggregates mixture voidage in compacted condition at some intermediate value of r_x.

Solving the equations system (12) yields the coefficients values:

$$a = \frac{P_{cr.s}r_x - P_{cr.s} + P_x - P_s r_x}{r_x^2 - r_x},$$

$$b = \frac{P_{cr.s} - P_{cr.s}r_x^2 - P_s r_x^2 + P_x}{r_x^2 - r_x}, \quad (13)$$

$$c = P_{cr.s}.$$

Nomograms for obtaining coefficients *A* and *b* in Eqs. 12 are given in Figure 2.

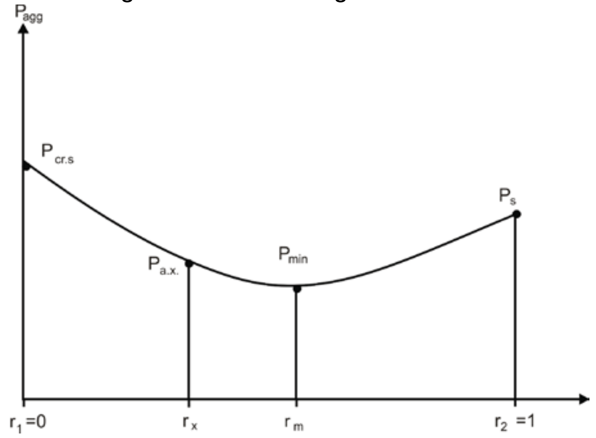

Figure1. Dependence between dry aggregates mixture voidage and the portion of sand in the sand – crushed stone mixture

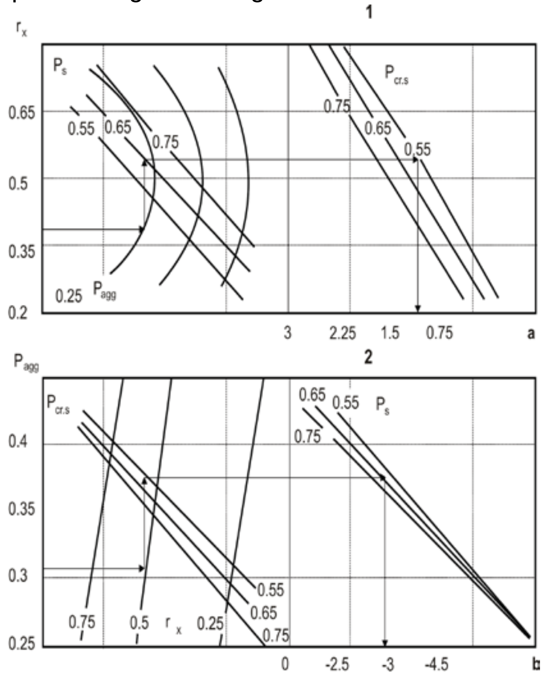

Figure 2. Nomograms for obtaining

Experimental voidage value for coarse and fine aggregates and their mixture can be easy found, knowing the real (ρ) and bulk (ρb) densities values: ($P_{agg} = 1 - \frac{\rho}{\rho_в}$).

Voidage of a dry concrete aggregates mixture can be calculated using a quadratic equation:

$$P_{agg} = ar^2 + br + P_{cr.s} . \tag{14}$$

Eq. (10) for calculating δ considering Eqs. (11) and (14) as well as taking into account the cement paste consumption for filling the aggregates pores (K_p) and the entrained air volume (V_{air}) can be presented as:

$$\delta = \frac{K_p V_{c.p} - \left(ar^2 + br + P_{cr.s}\right)\ \left(1 - K_p V_{c.p} - V_{air}\right)}{U_{cr.s} + (U_s - U_{cr.s})r} . \tag{15}$$

From $\partial\delta / \partial r = 0$ condition the corresponding nomogram for obtaining the optimal portion of sand in the aggregates' mixture r_{opt}^{δ}, providing the maximum thickness value (δ) at cement paste volume $V_{c.p}$ = const can be created (Figure 3).

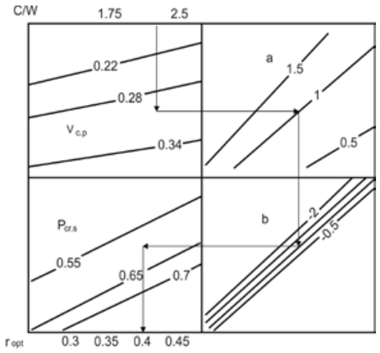

Figure 3. Nomogram for obtaining r_{opt}^{δ}

Note: The nomogram is prepared for crushed stone with specific surface of 6 cm²/cm³ and sand with specific surface of 160 cm²/cm³. If fine aggregate with lower specific surface is used, the values of r_{opt} should be increased by 0.01 per 20 cm²/cm³.

From Figures 4 follows that as $V_{c.p}$ increases, the design value of r_{opt}^{δ} decreases more sharply than the empirical optimal ones *r*. It can be explained by the fact that with an increase of $V_{c.p}$ due to higher C/W the growth of concrete mixture viscosity is not compensated in full by growth of δ (Figure 5).

Water demand constancy within some C/W range at given workability can be achieved just at corresponding correction of *r*.

Experimental values of r_{opt} are presented in Table 1 and Figure 5 were obtained for concrete mixtures with best workability for given compositions.

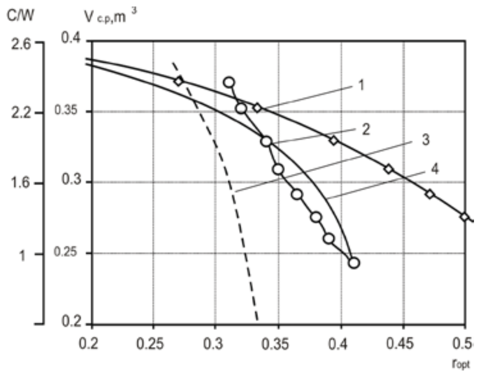

Figure 4. Dependence between optimal portion of sand in the aggregates mixture and the cement paste volume. 1 – ropt according to maximum δ condition (Figure 3). 2 – experimental values of ropt following [24]. 3 – experimental values of ropt following [23]. 4 – ropt values, considering $K_{C/W}$ coefficient

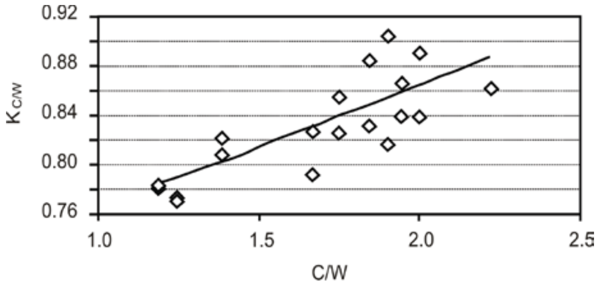

Figure 5. Regression dependence $K_{C/W}$ = f(C/W)

Following the data, given in Table 1, the optimal value of r_{opt} should be calculated according to the following equation:

$$r_{opt} = K_{C/W} r_{opt}^{\delta} \tag{16}$$

where $K_{C/W}$ – a coefficient, considering variations in concrete mixture's viscosity depending on C/W at δ = const.

Coefficient $K_{C/W}$ can be approximated by the following function:

$$K_{C/W} = K_1 e^{K_2 C/W} \tag{17}$$

where K_1 and K_2 are coefficients, depending on the initial materials features.

Table 1. Coefficient $K_{C/W}$ for calculating r_{opt}

No.	Consumptions of cement (C) and water (W), kg/m^3		C/W	Values of r_{opt}^{δ}	Exp. values of r_{opt}	$K_{C/W}$= r_{opt}/r_{opt}^{δ}	$K_{C/W}$ (Eq. 17)	$\Delta K_{C/W}$, %
	C	W						
Water demand of sand W_s = 7.5%								
1	250	180	1.39	0.460	0.37	0.804	0.803	0.14
2	250	200	1.25	0.429	0.34	0.768	0.790	2.82
3	250	210	1.19	0.413	0.32	0.775	0.784	1.20
4	350	180	1.94	0.409	0.35	0.856	0.859	0.33
5	350	190	1.84	0.391	0.33	0.870	0.848	2.47
6	350	200	1.75	0.372	0.31	0.807	0.839	3.92
7	350	210	1.67	0.351	0.29	0.770	0.831	7.91
8	400	180	2.22	0.379	0.34	0.870	0.888	2.03
9	400	200	2.00	0.337	0.29	0.860	0.864	0.51
10	400	210	1.90	0.313	0.27	0.862	0.855	0.83
Water demand of sand W_s = 9.5%								
11	250	180	1.39	0.455	0.37	0.835	0.800	4.21
12	250	200	1.25	0.422	0.33	0.783	0.787	0.53
13	250	210	1.19	0.403	0.32	0.794	0.778	1.95
14	350	180	1.94	0.399	0.34	0.853	0.833	2.35
15	350	190	1.84	0.379	0.32	0.845	0.854	1.04
16	350	200	1.75	0.357	0.30	0.869	0.822	5.46
17	350	210	1.67	0.333	0.28	0.842	0.836	0.75
18	400	180	2.22	0.365	0.32	0.876	0.892	1.80
19	400	200	2.00	0.317	0.27	0.853	0.844	0.95
20	400	210	1.90	0.288	0.25	0.832	0.850	2.07

For present experimental conditions K_1 = 0.68 , K_2 = 0.12.

Knowing r_{opt}, it is easy to calculate the coefficient, considering moving apart of coarse aggregate grains by cement-sand mortar K_s:

$$K_s = \frac{(V_{c.p} + rV_{agg})}{(1-r)P_{cr.s}V_{agg}}. \tag{18}$$

Characteristic design values of r_{opt} and K_s are given in Table 2.

Table 2. Optimal calculated values of sand portion in the aggregates mixture (r_{opt}) and moving apart coefficient (K_s).

Sl, cm	W, l/m³	C, kg/m³	$V_{c.p}$, m³	r_{opt}	K_s	$\delta \mu m$
15	232	400	0.36	0.26	1.41	33
	228	350	0.34	0.30	1.40	23
	225	300	0.32	0.33	1.38	17
	225	250	0.31	0.35	1.35	12
	225	200	0.29	0.36	1.31	8
10	221	450	0.37	0.25	1.43	40
	216	400	0.35	0.30	1.42	25
	210	350	0.32	0.34	1.41	18
	210	300	0.31	0.36	1.38	13
	210	250	0.29	0.37	1.34	8
	210	200	0.27	0.38	1.30	5
6	207	450	0.35	0.29	1.45	28
	200	400	0.33	0.34	1.44	20
	196	350	0.31	0.37	1.41	15
	195	300	0.29	0.39	1.38	10
	195	250	0.28	0.40	1.33	5
	196	200	0.26	0.40	1.29	2

Note: The data in this table is obtained for crushed stone with specific surface $U_{cr.s}$ = 6 cm²/cm³, $P_{cr.s}$ = 0.65, sand with U_s = 160 cm²/cm³, P_s = 0.65.

For high-slump concrete mixtures, applied for thin-walled, densely reinforced structures, underwater concreting, etc. the portion of sand in the aggregates' mixture is appointed considering water separation prevention (W_{sep}). With this aim known empirical recommendations are used [20, 22, 25].

Equating for calculating the maximum possible water quantity (W_k) kept by concrete mixture, can be presented as:

$$W_k = 1.65 \cdot N.C \cdot C + W_s r\left(1-V_{c.p}\right)\rho_s + W_{cr.s}\left(1-r\right)\left(1-V_{c.p}\right)\rho_{cr.s}. \tag{19}$$

where $N.C$ – cement paste normal consistency; C – specific consumption of cement; W_s and $W_{cr.s}$ – water demand of sand and crush stone; $V_{c.p}$ – the cement paste volume; ρ_s and $\rho_{cr.s}$ are the densities of sand and crush stone respectively.

Than assuming that $W = W_k$, it is possible to get a design equation for finding the required portion of sand r'_{opt} for preventing water separation in high-slump concrete mixtures:

$$r'_{opt} = \frac{W - 1.65 \cdot N.C \cdot C - W_{cr.s}\left(1-V_{c.p}\right)\rho_{cr.s}}{\left(W_s\rho_s - W_{cr.s}\rho_{cr.s}\right)\left(1-V_{c.p}\right)}. \tag{20}$$

At compositions proportioning it is expediently to find first r_{opt} from the best concrete mixture workability condition (minimal viscosity) and then if necessary to check the water separation possibility and to obtain the required value of r'_{opt} [1, 22].

Table 3 presents the values of r_{opt} and r'_{opt} for different concrete mixture compositions and experimental results for water separation, obtained following [24]. This data confirms the efficiency of providing of concrete mixtures water keeping capacity obtained by correcting the optimum sand content value.

Table 3. The optimal sand portion values for concrete mixtures ($N.C$ = 0.24, W_s = 7 %, $W_{cr.s}$ = 2 %)

No.	Consumptions of cement (C) and water (W), kg/m³		C/W	W_k, kg/m³	Values of r_{opt} following [24]	Optimal calculated values of r_{opt} and r'_{opt}	Water separation in concrete mixture, %
	C	W					
1	350	200	1.75	196	0.39	0.36 / -	-
2	350	210	1.67	188	0.4	0.34 / 0.37	2.6 / -
3	350	220	1.59	187	0.41	0.32 / 0.49	2.9 / -
4	400	200	2.00	204	0.37	0.34 / -	-
5	400	210	1.90	203	0.39	0.32 / -	-
6	400	220	1.82	202	0.4	0.29 / 0.3	0.6 / -
7	400	240	1.67	201	-	0.27 / 0.54	3.2 / -
8	450	210	2.14	218	0.37	0.32 / -	-
9	450	220	2.05	217	0.38	0.29 / -	-

Notes: 1. Numerator presents the values of r and water separation, calculated from the viewpoint of minimum viscosity (r_{opt}), denominator shows the (r'_{opt}) values according to Eq. (20). 2. "-" indicates that there is practically no water separation.

The air pores, involved at increasing the sand content in a concrete mixture, yield an essential increase of frost resistance, as at adding air-entrained admixtures. The main composition factor, affecting air entrainment in concrete without admixtures is the sand to cement ratio [20, 25]. Thus essential influence is contributed by W/C and grading of sand. It is known that the most active air-entraining sand fraction is 0.15…0.6 mm. Less than 0.07 mm in the size particles decrease air entrainment in the same measure, like cement [1]. At the same time 0.07…0.15 mm grains have little effect on air entrainment.

Complexity of the air- entraining mechanism and variety of influencing factors do not enable to develop general enough dependences [1, 18]. At the same time for specific initial conditions appropriate regression equations can be used for optimum concrete compositions design [14].

At the planning conditions given in Table 4 and experimental results (Table 5) the following square polynomial model of entrained air volume in coded variables was obtained by statistical processing [14] of the experimental data:

$$Y = 2.78 - 0.725X_1 - 0.313X_2 + 0.35X_3 + 0.45X_4 + 0.8X_5 + 0.275X_1^2 - \\ -0.09X_2^2 + 0.11X_3^2 + 0.05X_4^2 - 0.244X_5^2 - 0.07X_1X_3 - 0.1X_1X_4 + \\ +0.15X_1X_5 - 0.09X_3X_5 - 0.16X_4X_5 \quad (21)$$

Table 4. Conditions of experiments planning for investigating the effect of concrete mixtures compositions on entrained air content

Factors	Variation levels			Variation interval
	-1	0	+1	
Concrete mixture water demand (X_1), l/m³	160	195	230	35
Cement consumption (X_2), kgr/m³	250	375	500	125
Content of sand fraction less than 0.63 mm (X_3), %	30	55	80	25
Portion of sand in aggregates mixture (X_4)	0.3	0.4	0.5	0.1
Air-entrained admixture (X_5), %	0.0	0.015	0.03	0.015

The analysis of this model shows that in the chosen factorial space area the entrained air volume varies from 0.5 to 5.5 %, i.e. in a range being typical for concrete mixtures. In stiff mixtures of the entrained air volume increases 2…2.5 times without air-entrained admixture. Using air-entrained admixture additionally increases the entrained air volume by 40...60 %. Varying the sand content and its fractional composition at the same water content without air-entrained admixture enables to change the entrained air volume more than 2 times both in stiff and high-slump mixtures, increasing it up to 4.5 and 1.8 % accordingly.

Table 5. Planning matrix and air entrainment testing results

No.	Coded factors values					Entrained air volume (V_{air}), %		Slump Sl, cm	Vebe time Vb, s
	X_1	X_2	X_3	X_4	X_5	Exper.	Calc.		
1	+	+	+	+	+	2.61	2.72	18	—
2	-	-	+	+	+	4.92	5.13	—	13
3	-	+	-	-	-	2.7	2.57	—	5
4	+	-	-	-	-	1.98	2.08	22	—
5	-	+	-	+	+	3.81	3.67	—	7
6	+	-	-	+	+	2.52	2.78	20	—
7	+	+	+	-	-	2.10	2.02	21	—
8	-	-	+	-	-	3.91	4.03	—	10
9	-	+	+	+	-	4.46	4.51	—	9
10	+	-	+	+	-	3.41	3.34	17	—
11	+	+	-	-	+	1.54	1.46	18	—
12	-	-	-	-	+	3.11	3.19	—	9
13	-	+	+	-	+	3.58	3.41	—	7
14	+	-	+	-	+	2.49	2.64	19	—
15	+	+	-	+	-	2.26	2.16	17	—
16	-	-	-	+	-	4.18	4.29	—	11
17	+	0	0	0	0	2.19	2.33	22	—
18	-	0	0	0	0	3.63	3.78	—	8
19	0	+	0	0	0	2.41	2.38	5	—
20	0	-	0	0	0	2.88	3.00	7	—
21	0	0	+	0	0	3.19	3.24	6	—
22	0	0	-	0	0	2.60	2.54	8	—
23	0	0	0	+	0	3.14	3.28	5	—
24	0	0	0	-	0	2.29	2.38	8	—
25	0	0	0	0	+	3.41	3.34	8	—
26	0	0	0	0	-	1.77	1.74	7	—
27	0	0	0	0	0	2.76	2.78	7	—

The air-entrained admixture content, necessary for achieving the required entrained air volume can essentially change depending on the sand content in the concrete mixture and its grading. Interpolation calculations corresponding to Eq. (21) can be carried out using a nomogramm given in (Figure 7).

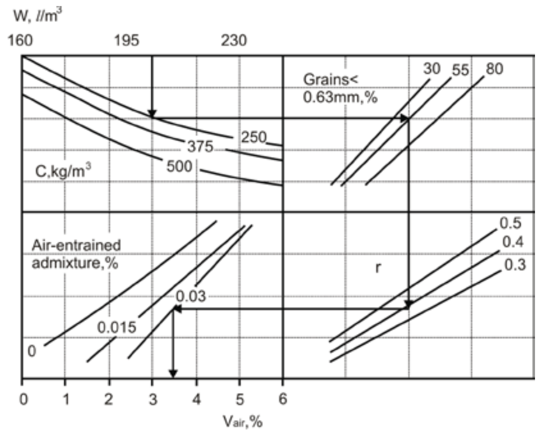

Figure 7. Nomogram for calculations the entrained air volume Vair depending on the concrete mixture composition factors

Usually, $r_{opt} \le r'_{opt} \le r''_{opt}$. At compositions proportioning, when it is expediently to obtain r'_{opt} and r''_{opt} corresponding water and cement contents correction, considering possible increase of the sand portion in the aggregates mixture, is required.

Thus, for multi parametric concrete compositions design problems the optimum sand content rule is that the optimal sand content in a concrete mixture provides in the best way the complex of given properties, and not just the mixture workability and concrete strength.

4. Conclusions

1. Based on the modified equation of viscosity of the concrete mixture, taking into account the effect of the cement-water ratio, voidness of the aggregate mixture and their specific surface, as well as the thickness of the cement paste layer on the aggregate grains, a method is proposed for calculating the optimal sand content that ensures the minimum water demand of the concrete mix.

2. The equations characterizing the amount of water kept by the concrete mixture, the calculated formula for the proportion of sand in the aggregate mixture, which prevents water separation, are substantiated.

3. A polynomial experimental-statistical model was obtained that allows calculating the required sand content for concrete mixtures of a particular workability depending on the required volume of entrained air, taking into account the water demand of the concrete mixture, cement consumption, sand fraction less than 0.63 mm and air entraining agent.

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