УДК 691.327

THE RULE OF CONSTANT CONCRETE MIXTURES WATER CONTENT AND ITS USING

ПРАВИЛО СТАЛОСТІ ВОДОПОТРЕБИ БЕТОННИХ СУМІШЕЙ ТА ЙОГО ЗАСТОСУВАННЯ

Dvorkin L.J., doctor of technical sciences, professor, Zhitkovsky V.V., candidate of technical sciences, ass. professor (National University of Water Management and Nature Resources Use, Rivne)

Дворкін Л.Й., д.т.н., професор, Житковський В.В., к.т.н., доц., (Національний університет водного господарства та природокористування, м. Рівне)

The article proposed modified T.Powers equation for cement systems. On the basis of this equation analytically substantiated rule of constant water content concrete mixtures used in the compositions design.
Experimentally shown that within certain limits change the amount of cements does not showing any changes concrete mixtures viscosity and workability.

Стаття присвячена теоретично-експериментальному обгрунтуванню правила сталості водопотреби, що використовується при проектуванні складу бетону для назначення необхідної витрати води. В результаті теоретичного аналізу обгрунтовано застосування модифікованого рівняння в'язкості Т.Пауерса для характеристики цементних систем (цементного тіста та бетоної суміші). Експериментально визначені показники в'язкості цементного тіста та бетонної суміші. На основі отриманих даних встановлені значення коефіцієнтів отриманого рівняння. Встановлено зв'язок між реологічними показниками та концентрацією цементу, заповнювачів їх пустотністю, питомою поверхнею, товщиною шару цементного тіста на зернах. Аналітично підтверджений гіпотетичний висновок про взаємну компенсацію в'язкостей цементного тіста та бетонної суміші у певному діапазоні витрат цементу.

Ключові слова:
Бетон, суміш, цементне тісто, водо цементне відношення, легковкладальність, в’язкість, розрахункова залежність.
Concrete, mixes, cement paste, water-cement ratio, water content, workability, viscosity, calculated definition.

1. Introduction The workability of concrete mixes and their water demand is determined primarily by the viscosity of concrete mixes. The value of viscosity is affected by a significant number of factors taken into account when designing concrete compositions. Obtaining the calculated viscosity dependence of concrete mixtures allows improving the existing technique of composition design and reducing the amount of experimental work. The studies, the results of which are given in this article, consisted in the experimental substantiation of the applicability of the T. Powers's modified viscosity equation of the concrete mixture to justify the rule of water demand constancy and the possibility on its basis of a calculated definition of the indices of workability and water demand.

Different equations were proposed for dispersion systems viscosity (η_{sm}). These equations are modifications of Einstein's formula [1]. One of the first researchers to propose a calculated dependence of the concrete mixtures viscosity was T. Powers [2]. This dependence has the form of an exponential equation:

$$\eta / \eta_0 = e^{K\varphi} , \quad (1)$$

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

This equation has, however, remained not investigated, and the physical meaning of coefficient K was not clear.

The rule of constant water content (RCWC) has been found in the beginning of 30th of the last century by I.Lyse [3] and F. McMillan in the USA [2]. 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 RCWC was applied only to low-slump mixtures. Later it was experimentally confirmed for no-slump and high-slump concrete mixtures.

Based on RCWC, graphs and tables for rough estimation of concrete mixtures water content, depending on cone slump and Vebe time were proposed [2-5]. Empirical recommendations for finding the concrete mixtures water content considering RCWC are presently used in heavy concrete proportioning methods, recommended in many countries [6].

Accepting the RCWC, various researchers use different values of limit cement consumption, for which this rule is valid. Most researchers suggest that the upper limit of RCWC applicability is 400 kg/m^3 [6], but some investigations show that it is valid up to 350 kg/m^3 and even up to 300 kg/m^3 [7]. As the concrete mixture stiffness (Vebe time) increase, both the lower and upper cement consumption limits decrease. Even within one stiffness (Vebe time) range the cement consumption varies from 280 to 380 kg/m^3 [5]. Non-considering essential variations of the upper cement consumption limit, caused by RCWC, decreases the accuracy of water demand calculation in many known procedures for concrete proportioning. Variations of the bottom limit cement consumption from 200 to 140 kg/m^3 practically do not affect the compositions design as such variations coincide with minimal cement consumptions range for normal-weidht concrete.

Essential stabilization of the upper limit of RCWC area and considering the features of cements [8], 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.
The RCWC proceed from a simplified picture of concrete mixture rheological properties changes depending on W/C. It was shown [9] 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 1 to 10 *Pa·s, than* at W/C change from 0.5 to 0.2 viscosity increases from 10 to 1000 *Pa·s* i.e. an two order magnitude higher. Variation of ultimate shear stresses is coordinated with RCWC even more. For mortar mixtures the shear stresses are $(4\ldots8)\cdot10^2$ Pa within the RCWC range and more than $2\cdot10^4$ Pa out the RCWC range.
The ultimate shear stress and viscosity of concrete mixtures, defining their workability parameters, unequivocally depend for constant materials on thickness of the cement paste film on aggregate grains δ and W/C. This conclusion was proved experimentally and theoretically [1, 10]. Concrete mixtures can be considered as roughly disperse structured systems, which rheological properties are defined both by quantity and viscosity of the dispersion medium, playing a role of peculiar hydrodynamical "greasing". As such greasing serves the cement paste, being a bingham liquid.

2. Materials and methods Dependence between viscosity of fine grain concrete mixture and volumetric concentration of aggregate was studied. The aggregate (quarts sand) having fineness modulus 2.1 was mixed with cement pastes having different W/C.
Portland Cement CEM II/A-S 32.5 N was used. The physical properties of the cement and clinker mineralogical composition are presented in Table 1.
The viscosity of cement pastes and sand concrete was measured using a rotational viscometer [11].
Rotary method based on measurement of viscosity of the material, placed between two coaxial surfaces and subjected to shear. Viscosity measurement is based on Newton's law presented as:

$$F = \eta \times \frac{d\vartheta}{d\gamma} \times S \qquad (2)$$

where F- the force of internal friction in a liquid layer with a surface S; ϑ - velocity of the fluid; γ - the direction perpendicular to the flow rate; η - viscosity.

3. Result and discussion The test results are given in Table 2 and Fig. 1, 2.
Experimental data (Table 2) allow presenting Eq. (1) as:

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

where K_o – proportionality coefficient ($K_o \approx 20$).
In turn the cement paste viscosity:

$$\eta_{cem.p.} = b e^{a \varphi_{cem}} , \quad (4)$$

Table 1.

Clinker mineralogic composition and cement properties

No.	Property	CEM II/A-S 32.5 N
1.	Specific surface (Blaine method), m^2/kg	280
2.	Setting time of cement: initial	1 h. 30 min.
3.	final	3 h. 50 min.
	Normal consistency of cement paste, %	26.4
4.	Ultimate strength at 28days, MPa	
5.	flexural	5.8
6.	compressive	42.5
	Clinker mineralogical composition, %	
1.	Tricalcium silicate	62
2.	Dicalcium silicate	20
3.	Tricalcium aluminate	6.5
4.	Tetracalcium alumina ferrite	11.5

where *a* and *b* – average empirical coefficients ($a = 19$, $b = 5.3 \cdot 10^{-4}$).

The volumetric concentration of cement in the cement paste is unequivocally characterized by the cement - water ratio:

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

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

Table 2.

Experimental and analytical values of cement paste and concrete mixtures viscosity

No.	C/W	φ_{cem}	Cement paste viscosity ($\eta_{cem.p}$), Pa·s		Devia-tion, %	φ_{agg}	Concrete mixture viscosity ($\eta_{c.m}$), Pa·s		Devia-tion, %
			Experi-mental	Calcu-lated			Experi-mental	Calcu-lated	
1	1.5	0.33	0.26	0.24	8.34	0.60	23.38	23.22	0.68
2	1.5	0.33	0.26	0.28	7.13	0.65	23.68	23.71	0.11
3	1.5	0.33	0.26	0.27	3.69	0.70	23.99	24.02	0.11
4	1.7	0.35	0.44	0.40	10.83	0.60	26.09	25.97	0.48
5	1.7	0.35	0.44	0.42	5.55	0.65	26.68	26.67	0.03
6	1.7	0.35	0.44	0.47	5.68	0.70	27.28	27.22	0.21
7	2	0.39	0.91	0.85	7.34	0.60	34.58	34.23	1.01
8	2	0.39	0.91	0.92	0.82	0.65	36.19	35.86	0.92
9	2	0.39	0.91	0.93	1.89	0.70	37.88	38.12	0.63
10	2.3	0.43	1.73	1.73	0.18	0.60	56.58	56.72	0.25
11	2.3	0.43	1.73	1.70	1.95	0.65	61.70	60.72	1.62
12	2.3	0.43	1.73	1.77	2.08	0.70	67.29	66.46	1.24

Notes: φ_{cem} is the volumetric cements concentration in cement paste; φ_{agg} is the volumetric aggregates concentration in concrete mixture.

Let express the aggregate volumetric concentration in a concrete mixture depending on conditional average thickness of the cement paste film (δ), considering, that $\delta = \frac{V_{c.p} - P_{agg} V_{agg}}{U_{agg}}$, where $V_{c.p}$, V_{agg}, U_{agg}, P_{agg} are the cement paste volume, cm^3/cm^3; volume, cm^3/cm^3; specific surface, cm^2/cm^3 and aggregates voidage, respectively.

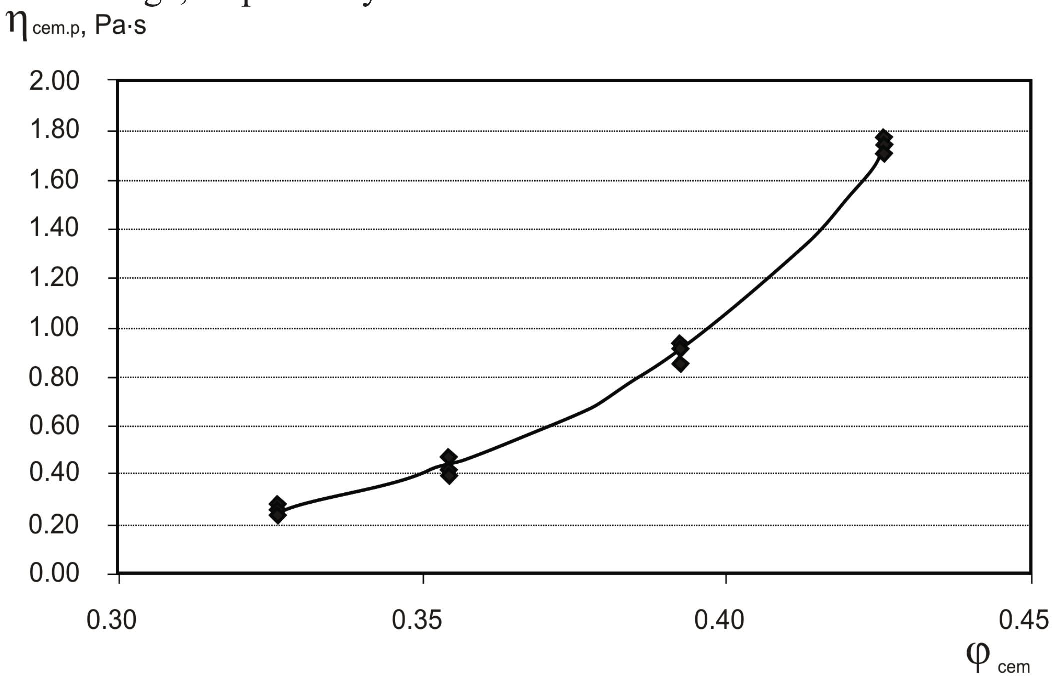

Fig. 1. Dependence between cement paste viscosity and volumetric cement concentration φ_{cem}

The aggregate volumetric concentration:

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

where $K_1 = (P_{agg} + 1)/P_{agg}$ 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:

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

As it follows from Eqs. (3 and 4), as the C/W increases, the cement paste viscosity increases exponentially and yields a corresponding growth of concrete mixture viscosity. At C/W = const the concrete mixture viscosity decreases as δ becomes higher.

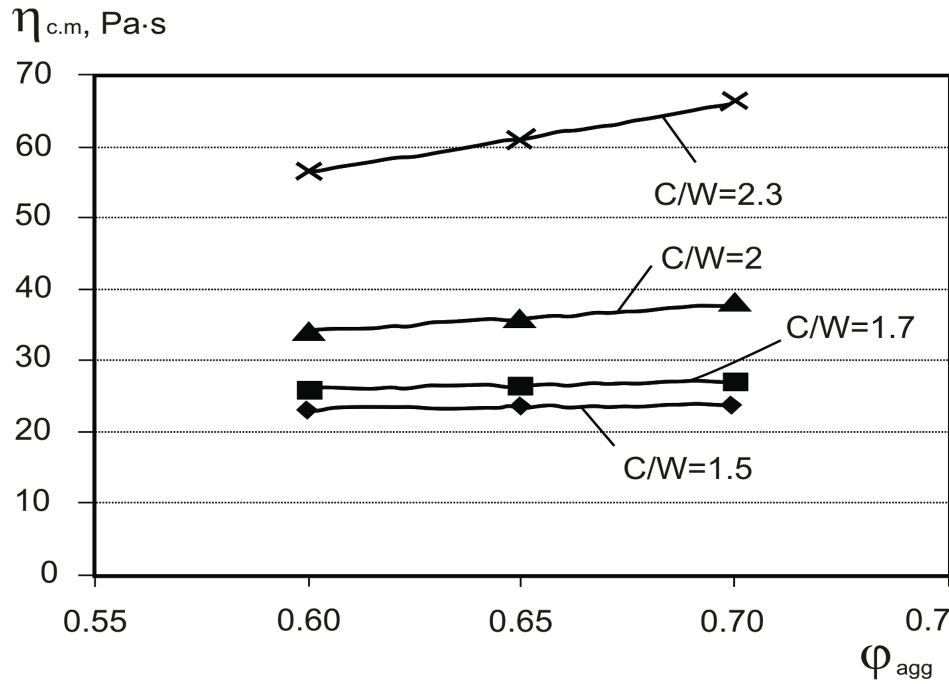

Fig. 2. Dependence between concrete mixture viscosity and voluetric aggregate concentration φ_{agg}

With C/W change up to a certain $(C/W)_{cr}$ the viscosity growth is compensated by higher cement paste film thickness, that creates some water demand stability range of a concrete mixture (Fig. 3).
It is confirmed analytically (Eq. (7)) confirms the hypothetical conclusion that in certain limits variation of cement paste quantity and its viscosity mutually compensate each other and viscosity of the entire system and consequently its workability remain constant. Let present the volumetric concentration of cement paste by volumetric water (V_w) and cement (V_{cem}) contents:

$$V_{c.p} = V_w + V_{cem} = V_w + V_w \frac{V_{cem}}{V_w}. \qquad (8)$$

Then dependence $\eta_{c.m} = f(\delta)$ at $W/C>(W/C)_{cr}$ and some optimum values of sand part in aggregates mixture can be transformed to dependence between concrete mixture viscosity and its water content (Fig. 4).

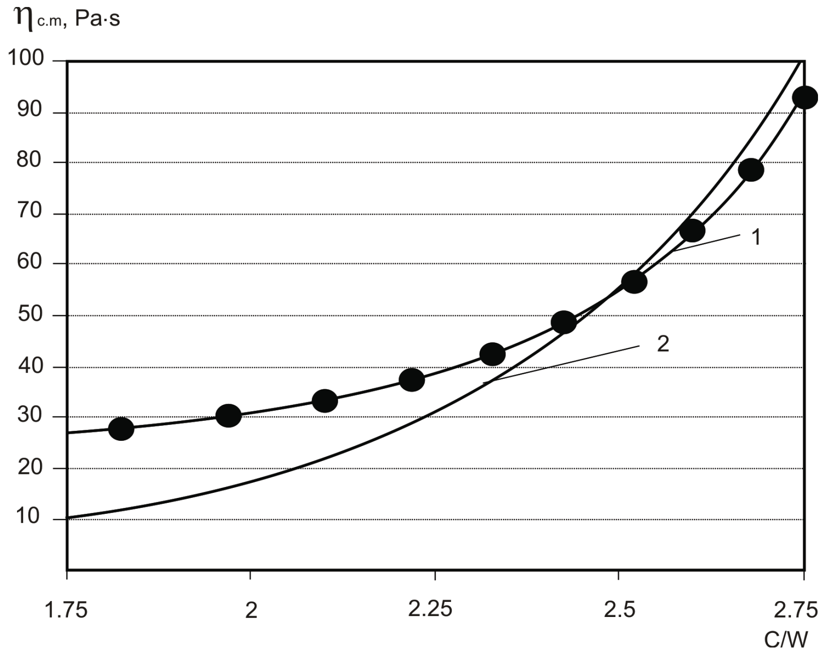

Fig. 3. Dependence between concrete mixture viscosity ($\eta_{c.m.}$) and C/W: 1 – according Eq. [7]; 2 – following (1)

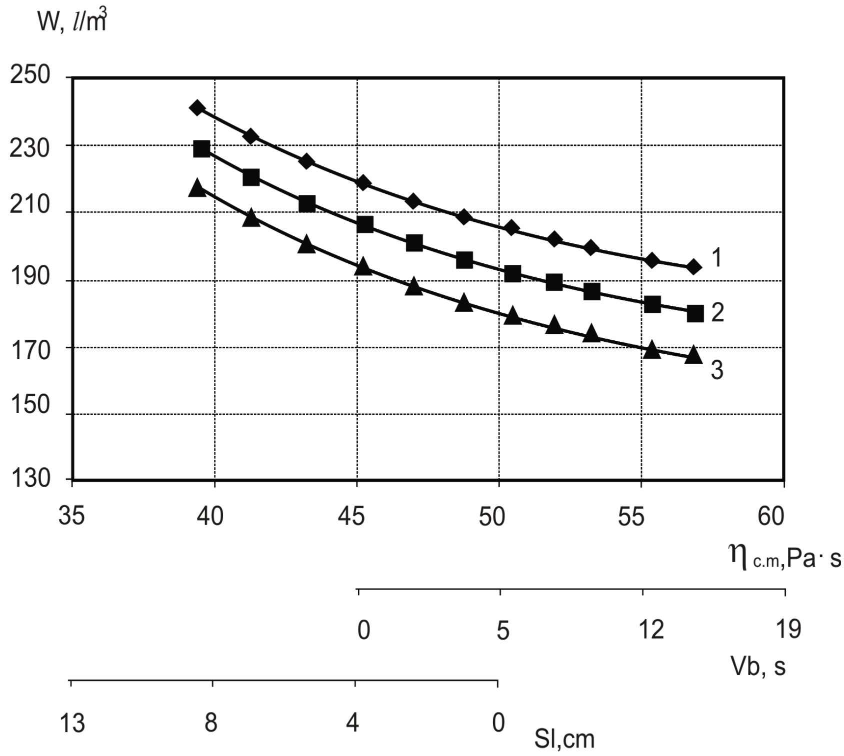

Fig. 4. Effect of concrete mixture viscosity on water demand: 1 – U_{agg} =70 m^2/m^3, P_{agg}= 0.6; 2 – U_{agg} = 70 m^2/m^3, P_{agg} = 0.5; 3 – U_{agg} = 70 m^2/m^3, P_{agg} = 0.4

The values of concrete mixture stiffness (Vebe, Vb) and cone slump (Sl) are in close connection with the viscosity parameter $\eta_{c.m}$ (Fig. 4). Dependencies Vb=$f(\eta_{c.m})$ and Sl =$f(\eta_{c.m})$ can be approximated by linear equations (7):

$$Sl = 44.6 - 0.9\eta_{c.m}, \quad (9)$$

$$Vb = 2.06\eta_{c.m} - 94.6. \quad (10)$$

Table 3 presents experimental values of workability parameter for fine grain concrete mixture and corresponding analytical values, calculated using Eqs. (9 and 10).

Table 3.

Viscosity and workability values of a fine grain concrete mixture

No.	Water deman, kg/m^3	$\eta_{c.m}$, Pa·s	Sl, cm		Deviation of exp. Sl values from calc., %	Vebe, s		Deviation of exp. Vb values from calc., %
			Exp.	Calc.		Exp.	Calc.	
1	180*	62	-	-	-	27	33	17
2	180**	57	-	-	-	26	23	14
3	190*	58	-	-	-	22	25	10
4	190**	52	-	-	-	11	13	9
5	200*	53	-	-	-	17	15	18
6	200**	47	1.8	2.3	22	-	-	-
7	210*	48	1.6	1.4	15	-	-	-
8	210**	44	4.4	5.0	12	-	-	-
9	220*	45	3.4	4.1	18	-	-	-
10	220**	42	7.5	6.8	10	-	-	-
11	230*	42	5.6	6.8	17	-	-	-
12	230**	39	10.5	9.5	11	-	-	-

* $U_{agg} = 70$ m^2/m^3; $P_{agg} = 0.6$; ** $U_{agg} = 70$ m^2/m^3; $P_{agg} = 0.5$.

Workability parameters are practically independent of W/C at W/C > $(W/C)_{cr}$, but change at different concrete mixtures water contents. Experimentally established that $(W/C)_{cr} \approx$ 1,65…1.68 N.C [12], than at N.C = 0.25…0.28 $(W/C)_{cr} \approx$ 0,43…0,45 and water content of 140…200 l/m^3 the limit cement consumption design diapason, for which the water demand constancy rule (RCWC) will remain valid, 325…445 kg/m^3.

Taking according to known recommendations [13] b = 0.42; α = 0.6…0.8 yields the design concrete W/C, providing practically zero capillary porosity.

At W/C < $(W/C)_{cr}$ its affect on cement paste and concrete mixture viscosity and ultimate shear stress sharply increases. To keep the workability parameters constant corresponding increase of the cement paste volume on aggregates grains due to water content growth is required. Out the RCWC limits increase of C/W on 0.1 yields about 1…2% higher water demand of the concrete mixture [14]. According to well known concrete proportioning methods [4, 7] it is recommended to correct the mixtures water content at cement consumption over 350 kg/m^3 or 400 kg/m^3 adding 1l for each 10 kg/m^3 of cement.

Conclusions. It is modified equation of concrete mixture viscosity T. Powers based on the results of the rheological studies of the effect on the viscosity of the cement paste and concrete mixture of cement and aggregates concentration, emptiness and a specific surface aggregates, conditional average thickness of the layer of cement paste in the aggregate grains. Eq. (7) analytically confirms the hypothetical conclusion that in certain limits variation of cement paste quantity and its viscosity mutually compensate each other and viscosity of the entire system and consequently its workability remain constant . The empirical equations for the slump and stiffness of concrete mixes are calculated, depending on the value of their viscosity.

1. Dvorkin O.L. Design of concrete compositions. (Basic theory and methodology), Rovno: NYVGP, 2003, 265 p. (in Russian).

2. Powers, T.C. (1968) The Properties of Fresh Concrete. John Wiley & Sons, New York, 533-652.

3. Lyse, I. (1932). Tests on consistency and strength of concrete having constant water content. Proceed, of the ASTM, 32, Part ii, pp 629-636.

4. Dvorkin L., Dvorkin O. Basics of concrete science. St.-Petersburg, Stroybeton, 2006, 686 p. (in Russian).

5. Bazhenov Y.M. Concrete technology. Moscow, ACB, 2003, 500 p. (in Russian).

6. T. C. Hansen, S. E. Hedegaard. Modified rule of constant water content for constant consistency of fresh fly ash concrete mixes. Materials and Structures, 1992, Volume 25, Number 6, Page 347.

7. Skramtayev B.G., Shubenkin P.F., Bazhenov Y.M. Methods for proportioning different types of concrete compositions. Moscow, Stroyizdat, 1966, 159 p. (in Russian).

8. Sizov V.P. Design of normal-weight concrete compositions. Moscow, Stroyizdat, 1980, 144 p. (in Russian).

9. Lea's Chemistry of cement and concrete. Ed. by Peter C. Hewlett, 4-th edition, Butterworth-Heinemann, 2004, 1092 p.

10. Dvorkin L.I. Optimal design of concrete compositions. Lvov, Vyshcha shkola, 1981, 159 p. (in Russian).

11. Bhatty J.I., Banfill P.F.G.. Sedimentation behaviour in cement pastes subjected to continuous shear in rotational viscometers. Cement and Concrete Research. Volume 12, Issue 1, January 1982, Pages 69–78.

12. Ahverdov I.N., Concrete phisics foundation, Moskow Stroyizdat, 1981, 464 p. (in Russian).

13. Sheykin A.E., Chechovskiy Yu.V., Brusser M.I. Structure and properties of cement concretes. Moscow, Stroyizdat, 1979, 344 p. (in Russian).

14. Soroker V.I., Dovzhik V.G. Steef concrete mixtures in precast reinforced concrete production. Moscow, Stroyizdat, 1964, 206 p. (in Russian).