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Method of proportioning the cement-water ratio of steam-cured concrete

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Abstract. The article presents the results of experimental studies that made it possible to substantiate the calculated dependences of the steam-cured concrete strength and the required values of the cement-water ratio (C/W) to ensure the specified strength values. For this purpose, dependences are obtained that are valid when using Portland cement and slag Portland cement, as well as a change in the wide range of regime parameters of heat treatment: temperature and duration of curing. To calculate the required values of C/W, a formula is justified, which allows determining the strength of cement under steaming when the temperature changes in the range of 60...95 C and the duration of isothermal heating during steaming from 4 to 18 hours. To calculate the strength of cement during steaming, the coefficients are recommended, which allow taking into account the content of aluminates and mineral additives in cement. Taking into account the calculated dependencies, an algorithm is proposed for calculating the C/W of steam-cured concrete and an example of its implementation.

1. Introduction

Wide experimental data on the effect of various steaming regimes [1–10], as well as the compositions of concrete mixtures, mineral and chemical additives [11–18] on the strength and other properties of concrete have been obtained in the works by many researchers, including those performed in recent years. However, the design method of proportioning of steam-cured concrete with a given strength, both instantly after steam curing and for certain duration of their subsequent hardening, considering a set of basic technological factors, has not been proposed in these studies. It leads in practice to the need for a sufficiently large amount of additional experiments in the proportioning of concrete mixes with required properties. The main task of the concrete mixes proportioning is determination the required cement-water ratio as the main parameter of the composition of concrete mixtures.

A number of calculated equations efor the steam-curing concrete compositions design was proposed in the works [2–4].These equations, obtained in the form of regression equations, are valid, but have a local character. Such equations are valid only in a certain interval of change of the factors taken into account.

S. Mironov and L. Malinina had showed [18] that at constant C/W concrete strength depends on the temperature, duration of the total heat cycle and subsequent curing. However, the required calculated dependencies had not been obtained by them, considering the activity of cements, steaming mode, and other technological factors. Concrete strength forecast after 4 h upon steaming (R_c^{st}) according to the normalized mode (2+3+6+2 h at 80 °C) with a certain cement activity after steaming (R_{cem}^{st}) was offered by L. Kaiser and R. Chekhova [19] using an empirical equation:

$$R_c^{st} = 0.41(R_{cem}^{st} + 9)C/W - 0.83\left(C/W\right)^2 - 0.35R_{cem}^{st} - 7. \qquad (1)$$

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It is difficult to apply equation (1) for the design of concrete compositions. This equation does not take into account the duration of hardening of concrete after steaming, the possible deviations of the steaming mode from the nominal one.

The dependence of the strength of cement concrete (R_c) based on cements of different mineralogical composition and the heat treatment time in hours at an isothermal aging temperature of 80° C was also established [19]. The samples were subjected to heat treatment with 3 + n + 2 hours modes and a preliminary exposure of 2 hours. They were tested 6 h after removal from the chamber. The established dependence is expressed by the formula:

$$R_c = A_{cem}\left(\lg\tau - \lg\tau_0\right), \tag{2}$$

where A_{cem} is parameter characterizing the influence of cement and test conditions, MPa;

τ is the heat treatment time in hours, including the isothermal exposure period n and part of the warm-up and cooling periods, during which the temperature of the samples exceeds 60 °C, on average $\tau = n + 3$;

τ_0 is induction hardening period i.e. the beginning of the formation of a solid structure.

The parameters of equation (2) for cements of different mineralogical composition are given in Table 1.

Table 1. Equation parameters (2) [19].

Cement group	Cement number	Mineralogical characteristic cement	A, MPA	τ_0, h	Limit of function linearity in h
I – low aluminate	1	C_3A = 2...3 %; C_3S = 60 %	12.5	0.6	20...25
	2	C_3A = 2...3 %; C_3S = 50 %	9.5	0.45	20
II – medium aluminate	3	C_3A = 8 %; C_3S = 60...65 %	10.0	0.15	9...10
	4	C_3A = 8 %; C_3S = 50 %	9.5	0.2	9...10
III – high aluminate	5	C_3A = 11...12 %; C_3S = 55 %	8.5	0.15	9
	6	C_3A = 11...12 %; C_3S = 40...50 %	7.0	0.18	7...8

As it can be seen from the Table 1, at an equal amount of C_3A, the strength characteristics of used cements (A) increase with increasing C_3S content in clinker. It grows with the decrease of the C_3A content at the equal amount of alite; the more C_3A content is, the shorter is the induction period. Cements of the I group have the minimal hardening rate of the steam cured concrete, the cement of the III group has the maximum one.

The optimal duration of isothermal exposure of concrete at 80...90 °C for the cements of all groups, above which the increase in strength becomes minimal, is 4...12 hours.

Recommended optimal modes of heat treatment of concrete (temperature rise – isothermal exposure, cooling in hours) on cements of various mineralogical groups [19] are given below:

Group I – 3 + 12 + 2;

Group II – 3 + 6 + 2;

Group III – 3 + 4 + 2;

Ordinary slag Portland cement – 3 + 14 + 2

Rapid hardening slag Portland cement – 3 + 8 + 2.

Most cements (except of the III group) provides intensive strength increase up to 28 days when steam cured in optimal conditions.

The strength of the steam cured concrete, considering the subsequent hardening up to 1 day (R_{c1}^{st}), can be determined from the equation proposed by V.I. Shein [20]:

$$R_{c1}^{st} = R_c^{st} + K_t I \lg(\tau_1 / \tau_0) R_c^{28}, \tag{3}$$

where I is the intensity of hardening of concrete after steam curing;

τ_1 is duration of hardening of concrete after steam curing (0.5…24 h);

τ_0 = 4 h;

R_c^{28} is concrete compressive strength in 28 days;

K_t is temperature coefficient (at average temperature of curing concrete 20 °C – K_t = 1.0; 30...40 °C – K_t = 1.1...1.2; 10 °C – K_t = 0.8.

Effective technological method of the increasing yield strength in the initial periods of hardening after steam curing is the introduction hardening accelerating additives into the fresh concrete [21].

Equations (2) and (3) should be used to predict the effect of the hardening duration of the steam-curing concrete, taking into account the steaming mode and the chemical and mineralogical composition of the cement. However, they do not allow to solve the main task of designing concrete mixes composition – finding the required C/W with the complex effect of cement strength in the conditions of steaming, steaming mode and the duration of following curing.

Obtaining the dependencies required to determine the compositions of the steam-curing concrete by the calculated-experimental method was the goal of this work. The creation of such dependencies develops as a theoretical understanding of the influence of the main technological factors on the properties of concrete. The development of such equations contributes to the creation of a calculation base for an express and practical available determination of concrete mixes composition that provide specified properties.

2. Materials and Methods

The studies were performed on cubic samples of concrete with dimensions 10×10×10 cm, which hardened both under normal conditions and steam curing. For the manufacture of concrete concrete mixes with slump 10...15 cm and stiffness V_b = 30...50 s have been used. Medium aluminate Portland cement CEM II/A-S (C_3A = 6...8 %, C_3S = 58...61 %), as well as slag Portland Cement CEM III/A were used as a binders. Both cements had a strength class of 42.5 N in accordance to European norms EN 197-1. The composition of cements and their physical-mechanical properties are given in Table 2.

Table 2. Composition and properties of used cements.

Cement	Cement composition, %		Setting time hour-min		Normal consistency, %	Compressive strength, MPa	
	clinker	slag	initial	final		7 days	28 days
Portland Cement	80	20	1-20	3-45	24.6	28.5	48.2
Slag Portland Cement	55	45	1-40	4-20	26.2	24.3	45.4

Quartz sand with a modulus of fineness M_f = 2.1 and granite crushed stone fraction 5–20 mm were aggregates of concrete. As a hardening accelerator sodium sulfate was added to concrete mixtures in an amount of 1 % by weight of cement.

Steaming of concrete samples was carried out in laboratory steaming chamber, which allows to regulate the temperature and duration of heat treatment within the required limits. The steaming temperature changed from 60 to 95 °C, the duration of isothermal heating from 2 to 18 h. After steaming, the samples were cooled for 2 hours.

3. Results and Discussion

Strength after thermal treatment (R_c^{st}) should be provided besides 28 days strength (R_c^{28}) for steam-cured concrete at proportioning, unlike normal hardening concrete. Given strength parameters can be achieved either at equal or at different C/W (Table 3). In the second case it is necessary to select C/W providing achievement of two given strength parameters. As shown in Table 3, C/W can vary, depending on the values of R_c^{28} and R_c^{st}, ratio between them, steaming period, duration of further hardening.

As it follows from Table 3, if the steaming period and duration of further curing is shorter, increase of strength after thermal treatment and prerequisites are created to R_c^{st} become the dominating strength parameter and vice versa. Applying high-early-strength cement, hardening accelerating admixtures and optimization the thermal treatment mode lead to narrowing the required C/W interval [19].

It is convenient to use the general equation for compressive strength 28 days to obtain required C/W:

$$R_c^{28} = pA_i\ R_{cem}\left(\frac{C}{W}-0.5\right), \tag{4}$$

where R_{cem} is cement compressive strength at 28 days of curing under normal conditions.

Table 3. Parameters, determining strength of steam-cured concrete.

No.	Steaming period, hours	Post-steaming period under normal conditions, hours	Design strength parameters/required C/W	
			Compressive strength after steam-curing and further curing, R_c^{st}, MPa	Design concrete strength, R_c^{28}, MPa
1	7	4	*14** 1.8	*20* 1.4
2	16	4	*14* 1.4	*20* 1.4
3	7	4	*21** 2.3	*30* 1.8
4	16	4	*21* 1.8	*30* 1.8
5	16	4	*15* 1.5	*30** 1.8
6	16	4	*25* 2.4	*40* 2.4
7	7	4	*35** 3.1	*50* 2.9
8	7	4	*25* 2.9	*50* 2.9
9	7	24	*35* 2.9	*50* 2.9
10	16	4	*25* 2.3	*50** 2.9

Notes: 1. The data is obtained for Portland cement with tricalcium silicate C_3A = 6…8 %, quartz sand of medium fineness and crushed granite stone size 5…20 mm. Concrete was steam cured at 80^0 according to the following mode 1+2+3.5+0.5 (total duration – 7 h) and 2+3+9+2 hours (total duration is 16 hours).

2. Required C/W values are given under the line.

3. * – dominant strength parameter.

For steam-cured concrete $pA_i = AA_1A_2\ldots A_n$ is a multiplicative coefficient, describing the initial materials features' influence (A), thermal treatment (A_1), hardening accelerating admixtures (A_2), etc.

The influence of various factors on A coefficient was widely investigated [21–23]. According to results of experimental data processing [17, 22, 23], coefficient A_1 for steam-cured concrete with compressive strength R_c^{28} up to 30 MPa varies from 0.85 to 0.95, for R_c^{28} > 30 MPa it is from 0.95 to 1.05. The lower values of A_1 are characteristic for shortened thermal treatment cycles and concrete mixtures with high water demand. The value of coefficient A_2 can be assumed according to known recommendations [22, 23].

We obtained the equations given below as the result of statistical processing of experimental data [17] for concrete with:

– 28-day compressive strength within the range of 20…30 MPa using Portland cement with strength of 40 MPa:

$$A_{\tau,t} = 0.242\ \ln(\tau) + 0.0115t + 0.008; \tag{5}$$

– 28-day compressive strength within the range of 30…40 MPa using Portland cement with strength 50…60 MPa:

$$A_{\tau,t} = 0.2179\ \ln(\tau) + 0.0134t + 0.063; \tag{6}$$

– 28-day compressive strength in the range of 20…30 MPa using blast-furnace slag cement with strength of 40 MPa:

$$A_{\tau,t} = 0.2395\ \ln(\tau) + 0.0111t - 0.06, \tag{7}$$

where τ is the hardening duration of hardening, days;

t is the average concrete temperature, °C (t = 5....40 °C).

The system of coefficients A_i can be specified by statistical processing of experimental data for a certain industrial enterprise. Table 4 presents an example of coefficients, characterizing effects of raw materials quality (A), hardening duration (A_τ), thermal treatment ($A_{t.t}$) and hardening accelerating admixtures (A_{ac}) on compressive strength of concrete, as well as calculated (R_c) and real (R_r) concrete strength values at C/W = 1.4 for Portland cement with strength 40 MPa.

Table 4. Values of coefficients A_i, calculated (R_c) and real (R_r) concrete strength values (R_{cem} = 40 MPA, C/W = 1.4).

Type of concrete	Age of hardening	Coefficients					R_c, MPa	R_r, MPa
		A	A_τ	$A_{t.t.}$	A_{ac}	pA		
Normally hardened concrete	7 days	0.53	0.65	–	–	0.34	12.4	14.5
	28 days	0.53	–	–	–	0.53	19.1	15.3
	90 days	0.53	1.20	–	–	0.64	22.9	25.2
	180 days	0.53	1.35	–	–	0.72	25.8	21.9
Concrete steam-cured at 80 °C, steam-curing mode (2+3+6+2 h)	4 h	0.53	–	0.63	–	0.33	12	13.9
	12 h	0.53	–	0.71	–	0.38	13.5	11.5
	24 h	0.53	–	0.75	–	0.4	14.3	12.7
Same, with hardening accelerating admixture of sodium sulfate	4 h	0.53	–	0.63	1.3	0.43	15.4	17.5
	12 h	0.53	–	0.71	1.25	0.47	17	19
	24 h	0.53	–	0.75	1.2	0.48	17.3	19.7

Deviations of calculated strength values from average experimental ones do not exceed 17 %, which is acceptable for the calculations at the design stage of the mix's compositions.

Strength of concrete after steaming (R_c^{st}) varies in a wide range, thus the dominant factors, are cement-water ratio (C/W) and cement strength at the given thermal treatment cycle (R_{cem}^{st}).

it is rational to express the steam-cured concrete strength R_c^{st} as well as R_c^{28} using Bolomey formula for porportioning:

$$R_c^{st} = \rho K\, R_{cem}^{st}\left(C/W - b\right), \qquad (8)$$

where $K = K\, K_1\, K_2\, K_3 \ldots K_n$ is a multiplicative coefficient, considering the influence of various factors on strength of steam-cured concrete (K is the basic coefficient, characterizing the impact of R_{cem}^{st};

K_1 is coefficient, depending on concrete mixture workability;

K_2 is coefficient, taking into account the impact of steam-cured concrete aggregates;

K_3 is coefficient, considering strength growth due to hardening accelerators addition).

It is acceptable to use Equation (8) for approximating the data, calculated according to Equation (1), (see Table 5). The values of basic coefficient K vary depending on R_{cem}^{st} within the range 0.5–0.67. By applying average values of the coefficient K = 0.66 for R_{cem}^{st} = 20–25 MPa and K = 0.53 for R_{cem}^{st} = 30–40 MPa [19] the deviations in the values of R_{cem}^{st} calculated according Equations (1), (8) were below 10 %.

Table 5. Calculated values of R_c^{st}, MPa.

R_{cem}^{st}, MPa	Equation	C/W						
		1.55	1.80	2.00	2.30	2.60	2.80	3.00
20	(1)	10.7	14.3	17.1	21.2	25.1	27.6	30.1
	(8) K = 0.66; b = 0.74	10.6	13.9	16.6	20.5	24.5	27.1	29.8
25	(1)	12.1	16.2	19.4	24.1	28.7	31.6	34.5
	(8) K = 0.66; b = 0.74	13.3	17.4	20.7	25.7	30.6	33.9	37.2
30	(1)	13.5	18.2	21.8	27.1	32.3	35.6	38.9
	(8) K = 0.53; b = 0.74	12.9	16.9	20.1	25.0	29.8	33.0	36.2
40	(1)	16.4	22.0	26.5	33.0	39.4	43.6	47.7
	(8) K = 0.53; b = 0.74	17.2	22.6	26.9	33.3	39.7	44.0	48.3

Note: Coefficients K and b have been obtained by analyzing linear dependencies $R_c^{st} = f(R_{cem}^{st}, C/W)$ following the data given in [19].

Coefficient b in Equation (8) varies insignificantly for the entire range of R_c^{st} values of the concrete compositions (Table 5) and it is equal to 0.74. Coefficient K decreases as the steamed cement strength increases (Table 5), it shows that the influence of the last one on concrete strength is nonlinear. This conclusion follows also from Equation (1).

The values of coefficient K, given in Table 5, are valid for low-slump fresh concrete, based on crushed stone and medium grained sand. Water content and correspondingly workability, which can be considered in Equation (8) by coefficient K_1 have significant impact on strength of steam-cured concrete at constant C/W. For concrete with slump Sl = 1–4 cm the value of K_1 = 1, and with $Sl \geq 9$ cm – K_1 = 0.9, if Vebe time V_b = 30–50 sec then K_1 = 1.1 (Table 6).

Table 6. Experimental and calculated values of concrete strength after steaming.

No.	Concrete strength R_c^{st}, MPa	C/W						
		1.55	1.80	2.00	2.30	2.60	2.80	3.00
R_{cem}^{st} = 20 MPa; Sl = 10–15 Cm								
1	Experimental values	9.9	13.4	14.5	19.1	22.7	23.8	27.3
2	Calculated according to Equation (8) at K_1 = 0.9	9.6	12.6	15.0	18.5	22.1	24.5	26.8
R_{cem}^{st} = 40 MPa; Sl = 10–15 Cm								
3	Experimental values	16.7	20.6	24.4	31.9	36.7	41.8	45.9
4	Calculated according to Equation (8) at K_1 = 0.95	16.3	21.3	25.4	31.4	37.5	41.5	45.5
R_{cem}^{st} = 20 MPa; V_b = 30–50 sec.								
5	Experimental values	10.5	14.8	17.7	23.5	27.6	28.5	31.1
6	Calculated according to Equation (8) at K_1 = 1.1	11.8	15.4	18.3	22.7	27.0	29.9	32.8
R_{cem}^{st} = 40 MPa; V_b = 30–50 sec.								
7	Experimental values	17.4	23.8	29.8	35.7	42.8	48.8	52.1
8	Calculated according to Equation (8) at K_1 = 1.1	18.9	24.7	29.4	36.4	43.4	48.0	52.7

Notes: 1. Experimental data have been obtained using Portland cement (tricalcium aluminate content C_3A = 6…8 %), medium grained quartz sand and crushed granite stone 5…20 mm. Concrete was steamed at 80 °C according to cycle (2)+3+6+2 h.

2. The average deviation of calculated values K_1 from the experimental ones does not exceed 5 %.

The steam-cured concrete aggregates features can make influence on water-content variation and directly on the change of C/W to achieve required strength. In the last case coefficient K_2 is added to Equation (8). For ordinary aggregates K_2 = 1. However, it can be assumed that K_2 = 0.95 if crushed stone or gravel has reduced strength as well as if the content of weak grains or clay, silt and dust content is rather high; K_2 = 0.9 for sand with fineness modulus below 1.5.

The essential reserve for C/W reduction of steam-cured concrete can be provided by strength growth due to hardening accelerators, considered by coefficient K_3 in Equation (8), and further hardening after thermal treatment.

Processing the experimental results obtained when the concrete samples were kept at 20 °C for 0.5–24 hours after steaming ($\tau_{p.p}$) using the 2 + 3 + τ_{iz} + 2 mode (τ_{iz} is the isothermal aging per hour) at t = 80 °C allowed us to calculate the nomogram for determination the change in the concrete strength after the heat treatment (Figure 1) within the range 0.5–24 h after steaming at different duration from equation:

$$R_{c1}^{st} = R_c^{st} + \Delta R_c R_c^{28}. \tag{9}$$

At $\tau_{p.p}$ = 1 – 28 days the intensity of concrete strength growth is practically independent of steaming mode parameters. Concrete strength at this hardening interval can be found according to the following formula:

$$R_{c_2}^{st} = R_{c_1}^{st} + K_t \frac{R_c^{28} - R_{c_1}^{st}}{\lg 28} \lg \tau_{p.p}. \tag{10}$$

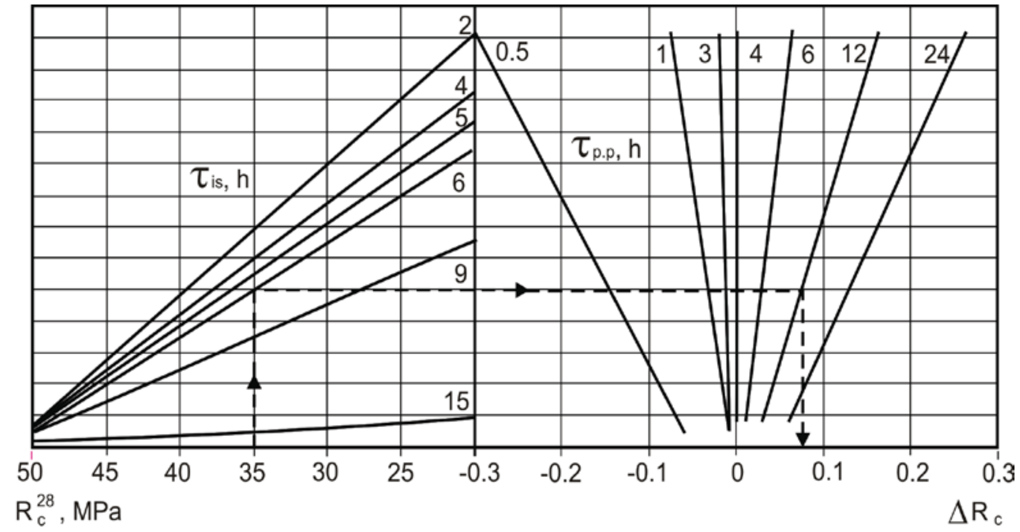

Figure 1. Nomogram for calculation of increase in relative concrete strength ΔR_c^{st} after steaming and post-steaming period up to 1 day.

Cement strength at steaming (R_{cem}^{st}) can be expressed as:

$$R_{cem}^{st} = R_{cem} K_e, \tag{11}$$

where K_e is efficiency coefficient, characterizing the influence of different technological factors on strength of standard cement – sand specimens at W/C = 0.4 after thermal treatment.

The K_e value determined for steaming standard cement – sand mortar specimens varies depending on the applied cement from 0.55 to 0.75.

Corresponding graphs (Figure 2) of basic efficiency coefficient K_e^0 depending on isothermal heating duration τ_{is} and temperature $t_{t.t}$ for Portland cement with strength of 50 MPa $(K_{e_{p.c}}^0)$ and blast furnace slag cement with strength of 40 MPa $(K_{e_{s.p.c}}^0)$, obtained by experimental data processing are given below [19].

Cements have been made of typical medium aluminate clinker (tricalcium aluminate C_3A = 6.2–7.1 %, tricalcium silicate C_3S = 58.5 – 61.3 %) and additionally included: Portland cement – 5 % of gypsum, blast furnace slag cement – 5 % of gypsum and 50 % of blast furnace slag. Cement strength at steam curing was obtained 4 h after thermal treatment (steam-curing cycle 2 + 3 + τ_{is} + 2). The steam curing temperature was varied from 60 to 95 °C, τ_{is} from 2 to 18 h. The value of K_e^0 was found from the condition that $K_e^0 = R_{cem}^{st} / R_{cem}$.

Table 7 presents the experimental and calculated values of K_e^0, obtained according to Figure 2. Analysis of the calculated and experimental values of K_e^0 shows their high convergence.

The most influential factors, effecting K_e, are chemical-mineralogical composition, mineral admixtures content and cement strength:

$$K_e = K_A K_D K_{R_{cem}} K_e^0, \tag{12}$$

where K_e^0 is the basic efficiency coefficient value that can be found using Figure 2;

K_A, K_D, K_{Rcem} are correcting coefficients, depending correspondingly on aluminate content in cement, mineral admixtures content and cement strength.

Considering the data given in [18, 19], there are following values of K_A: for high aluminate cements at $\tau_{is} \le 3$ h K_A = 0.9; $\tau_{is} \ge 6$ h; K_A = 0.8 for low aluminate cements at $\tau_{is} \le 3$ h K_A = 0.8; $\tau_{is} \ge 6$ h K_A = 0.95; $\tau_{is} \ge 9$ h; K_A = 1 – 1.1.

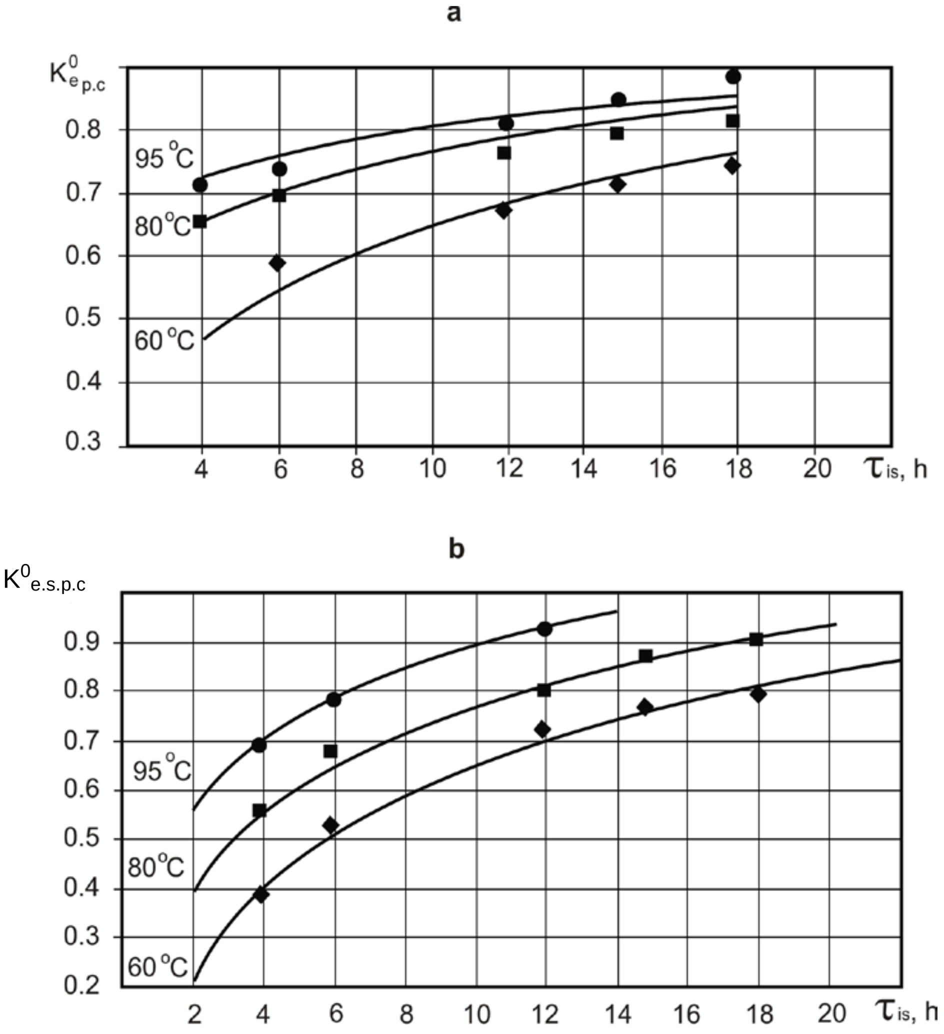

Figure 2. Graphs for determining coefficients K_e^0 : *a* – Portland cement; *b* – blast furnace slag cement; ◊ – $t_{t.t}$ = 60°C; □ – $t_{t.t}$ = 80 °C; ○ – $t_{t.t}$ = 95°C.

Table 7. Calculated and experimental values of K_e^0 and relative strength values.

K_e^0 and relative strength values	Steam curing temperature, °C, $t_{t.t}$	Isothermic heating duration τ_{is}, h.				
		4	6	12	15	18
Portland cement with tricalcium aluminate content C_3A = 6…8 % (authors data)						
Calculated values of K_e^0	60	0.48	0.56	0.70	0.74	0.78
	80	0.63	0.69	0.78	0.81	0.83
	95	0.75	0.78	0.84	0.86	0.87
Experimental values of K_e^0	60	0.51	0.59	0.67	0.72	0.75
	80	0.63	0.69	0.76	0.78	0.81
	95	0.71	0.74	0.81	0.86	0.89
Blast furnace slag cement (authors data)						
Calculated values of K_e^0	60	0.40	0.51	0.70	0.76	0.81
	80	0.55	0.65	0.82	0.87	0.92
	95	0.67	0.75	0.91	0.95	–
Experimental values of K_e^0	60	0.39	0.52	0.71	0.76	0.8
	80	0.55	0.66	0.81	0.87	0.91
	95	0.69	0.78	0.94	0.97	–
Portland cement with tricalcium aluminate content C_3A = 6…8 % [18]						
Experimental values for relative strength of concrete at W/C = 0.4 (R_c^{st} / R_c^{28})	60	0.5	0.6	0.76	0.8	0.83
	80	0.67	0.76	0.87	0.88	0.88
	100	0.70	0.72	–	–	–
Blast furnace slag cement [18]						
Same	60	0.4	0.49	0.67	0.74	0.8
	80	0.55	0.64	0.84	0.9	0.92
	100	0.7	0.8	–	–	–

The value of coefficient K_D depends on mineral admixtures' type and content. If the mineral admixtures' content is up to 10 % the cement strength at steam curing is usually constant. At a 20 % mineral admixtures' content a certain reduction of R_{cem}^{st} is observed at shortened steam-curing cycles. At $\tau_{is} \leq 4$ h adding 20 % of blast furnace slag and fly ash to cement leads to average strength decrease at 10 % (K_D = 0.9), pozzolanic admixtures – 15 % (K_D = 0.85) [24]. At $\tau_{is} > 4$ h – K_D = 1.0.

For cement with 28-day strength of 50 MPa K_{Rcem} = 1, 40 MPa K_{Rcem} = 1.05; 30 MPa K_{Rcem} = 1.15; 55 MPa K_{Rcem} = 0.95.

The scheme of the algorithm for calculation C/W of steam-cured concrete is presented in Figure 3. The described set of calculation dependencies enables to obtain the required cement-water ratio (C/W) at different requirements to concrete under thermal treatment and different hardening duration, as well as estimate the efficiency of technological solutions, related to varying the temperature, isothermal duration, hardening after steaming, etc.

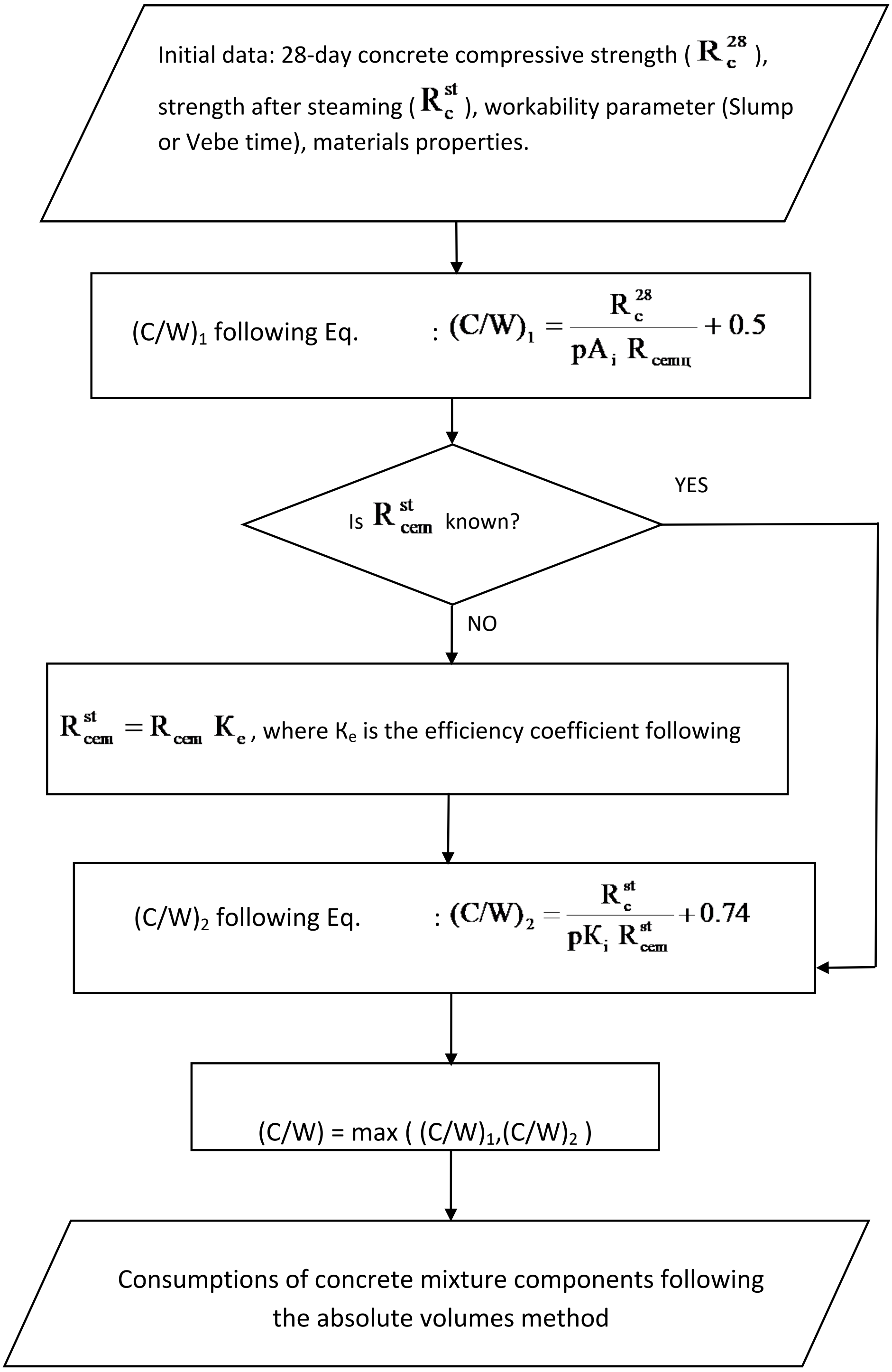

Figure 3. Algorithm for calculation of steam-cured concrete C/W.

Example

To determine C/W and achieve compressive strength of concrete 28 MPa after steaming and further hardening of 1 day, while ensuring design strength of 28 days 40 MPa.

Initial data: slump of fresh concrete – 10–15 cm, steaming mode – 2+3+6+2 at 80 °C.

Materials: Portland cement CEM II/A-S (C_3A = 8 %, C_3S = 6 0 %) strength class 42.5 N (design strength 50 MPa), crushed stone 5–20 mm, sand with fineness modulus 2.1.

Accept A = 0.55 in the Equation (4) and determine (C/W_1), to achieve given concrete strength in 28 days:

$$C/W_1 = \frac{R_c^{28}}{AA_1R_{cem}} = \frac{40}{0.55 \cdot 1 \cdot 50} + 0.5 = 1.95.$$

The value of the basic coefficient of steaming efficiency is taken according to Figure 2.

$$K_0^e = 0.7.$$

Values of correction coefficients:

$$K_A = K_D = K_{R_{cem}} = 1.$$

Calculate the value K_e considering the influence of the mineralogical composition of cement, the content of mineral additives and the activity of the cement according to the formula (12):

$$K_e = K_A K_D K_{R_{cem}} K_e^0 = 1 \cdot 1 \cdot 1 \cdot 0.7 = 0.7.$$

Cement strength after steaming, according to (11):

$$R_{cem}^{st} = R_{cem} K_e = 50 \cdot 0.7 = 35 \text{ MPa}.$$

Value of ΔR according to Figure 1:

$$\Delta R = 0.1.$$

Strength of concrete in 4 h after steaming Equation (9):

$$R_c^{st} = 28 - 0.1 \cdot 40 = 24 \text{ MPa}.$$

Find (C/W)$_2$ according to the Equation (8) to achieve of necessary concrete strength after steam curing:

$$(C/W)_2 = \frac{R_c^{st}}{pKR_{cem}^{st}} + 0.74 = \frac{24}{0.53 \cdot 1 \cdot 1 \cdot 35} + 0.74 = 2.03.$$

Since $(C/W)_2 > (C/W)_1$ we accept C/W = 2.03 for further calculations of the concrete composition.

4. Conclusions

1. The equations of concrete strength are experimentally substantiated, which allow taking into account the steaming mode and the duration of the subsequent hardening up to 28 days.

2. Multiplicative coefficients, taking into account the complex of basic technological factors, proposed quantitative dependencies and recommendations for calculating these coefficients are included in the equation of strength of concrete immediately after steaming and after 28 days of hardening.

3. As a result of processing the experimental data, a nomogram was drawn to calculate the strength of concrete at the age of 0.5–24 h after steam curing. Equation for calculation of the increase in concrete strength after steam curing at the age of 1–28 days was also suggested.

4. The equation for determination the activity of Portland cement and blast furnace slag cement developed during steam curing has been substantiated, taking into account cement activity during normal hardening and the coefficient reflecting the effect of temperature and the duration of isothermal holding of concrete during steaming (coefficient of steaming efficiency). Graphical dependencies are recommended to find this coefficient.

5. The combination of the obtained quantitative dependencies and recommendations allows to find the values of the required cement-water ratio for steam-cured concrete in accordance with the suggested algorithm, under given conditions.

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Метод расчета цементно-водного отношения пропариваемого бетона

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Ключевые слова: цементно-водное отношение, прочность, температура, пропаривание, твердение, режимы

Аннотация. В статье приведены результаты экспериментальных исследований, позволившие обосновать расчетные зависимости прочности пропаренного бетона и необходимых значений цементно-водного отношения (Ц/В) для обеспечения заданных значений прочности. С этой целью получены зависимости, справедливые при применении портландцемента и шлакопортландцемента, а также изменении в широком диапазоне режимных параметров тепловой обработки: температуры и длительности последующего тведения. Для расчетов необходимых значений Ц/В обоснована формула, позволяющая определить активность цемента в условиях пропаривания при изменении температуры в диапазоне 60…95 °C и длительности изотермического прогрева при пропаривании от 4 до 18 часов. Для расчета активности цемента рекомендованы для условий пропаривания также коэффициенты, позволяющие учитывать алюминатность цемента, вид и содержание в цементе минеральных добавок. С учетом полученных расчетных зависимостей предложен алгоритм для расчета Ц/В пропаренных бетонов и пример его реализации.

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