Open Access

*Recent Progress in Materials*

Research Article

# Accounting for the Influence of Heat-Moisture Treatment Mode When Designing Concrete Composition

Leonid Dvorkin [†, *], Vadim Zhitkovsky [†], Ruslan Makarenko [†]

National University of Water and Environmental Engineering, Rivne, Ukraine; E-Mails: l.i.dvorkin@nuwm.edu.ua; v.v.zhitkovsky@nuwm.edu.ua; r.m.makarenko@nuwm.edu.ua

† These authors contributed equally to this work.

* **Correspondence:** Leonid Dvorkin; E-Mail: l.i.dvorkin@nuwm.edu.ua

**Academic Editor:** Mostafa Seifan

**Special Issue**: New Trends on Construction Technologies and Sustainable Building Materials

*Recent Progress in Materials*
2023, volume 5, issue 1
doi:10.21926/rpm.2301009

**Received:** January 12, 2023
**Accepted:** February 20, 2023
**Published:** February 24, 2023

## Abstract

The article proposes a method that considers the parameters of heat and moisture treatment of concrete when designing its composition. Based on the analysis of experimental data, formulas are proposed that allow taking into account the type and characteristics of cement, the characteristics of aggregates, the effect of temperature and duration of steaming, and the water-cement ratio. Graphs and nomograms have been obtained, which makes it possible to simplify the calculation procedure according to the proposed method. Typical numerical examples of the application of this technique are given.

## Keywords

Concrete; steaming; water-cement ratio; strength; design

## 1. Introduction

In concrete composition designing, experimental and calculation-experimental methods are used [1-3]. The calculation-experimental method involves a preliminary determination of the concrete composition using basic calculated dependencies, followed by adjustment of these compositions in laboratory batches. Compared with the experimental method, this method significantly reduces labor costs and time for determining concrete composition with specified normalized parameters in specific production conditions.

For normal-weight concrete produced under normal temperature conditions, the basic design dependencies are the dependences of the concrete strength on the water-cement (W/C) or cement-water (C/W) ratio, based on Feret, Abrams, Powers, Bolomey and modified by other researchers [3]. Calculating the required cement-water ratio for steamed concrete becomes much more complicated, especially in achieving the required concrete strength immediately after steaming. As shown by practical experience and many studies [3-13], the strength of concrete after steaming is significantly affected by its mode parameters. It affects both the value of the cement strength realized in concrete and the required C/W to achieve a given strength.

In [14], after studying the concrete strength of 40 batches of cement of various types, strength classes and chemical-mineralogical composition, an strength equation was proposed depending on the cement strength and C/W. At the same time, the concrete strength and the Portland cement used in it were considered after steaming in one mode (2 + 3 + 6 + 2 (hours) at 80°C (for Portland slag cement 90°C)). An analysis of the formula proposed in this paper [14] shows that at C/W <3, a linear dependence for compressive strength is practically maintained. For C/W >3, it is proposed to introduce an average correction for the nonlinearity of this dependence.

An actual task in the steamed concrete compositions design is to consider the kinetics of its hardening after heat treatment. Known dependencies [11], based on the logarithmic law of concrete strength increase in time, as applied to steamed concrete, require clarification.

Summarizing the state of the problem of developing design dependencies necessary for the implementation of the calculation-experimental method for designing compositions of steamed concretes, we can state that it requires additional research. This article presents the results of a study aimed at developing the parameters of the concrete composition, considering the mode parameters of heat and moisture treatment and other technological factors.

## 2. Materials and Methods

The studies were carried out by analyzing the data in the works [11, 13, 14] and approximating these data using empirical equations. To confirm the equations obtained, an experiment was carried out, which consisted in studying the effect of steaming parameters (holding time before steaming, temperature and duration of isothermal heating) on the strength characteristics of standard cement-sand samples (according to EN 196-1 [15]) and normal weight concrete (according to EN 12390-1 [16]).

Portland cement and slag cement were used in the research. The cement is made based on 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, Slag Portland cement - 5% of gypsum and 50% of blast furnace slag. The following characteristics were determined: compressive strength 4 hours after steaming, compressive strength 28 days after steaming, and strength under normal conditions at different ages. The steaming of cement and concrete was carried out in a laboratory steaming chamber according to the following regime: holding until steaming - 2 hours, raising the temperature - 3 hours, isothermal holding ($\tau_{is}$) - varied from 2 to 18 hours, cooling - 2 hours (2 + 3 + $\tau_{is}$ + 2). The steaming temperature varied from 60 to 95°C.

Concrete samples (cubes 100 × 100 × 100 mm) were made using medium-grained sand and crushed granite stone 5…20 mm. The concrete C/W was changed in the range from 1.55 to 3.

## 3. Results and Discussion

In the practice of calculating C/W when designing the concrete composition [11], the following formula is widely used:

$$\mathrm{R_{cmp}} = \mathrm{AR_{cem}}(\mathrm{C/W} - \mathrm{b}), \tag{1}$$

where $R_{cmp}$ is concrete compressive strength; $R_{cem}$ is the 28-day cement strength, obtained by testing of the standard cement-sand mortar samples; A and b are an empirical coefficients.

An increase in the resolution of the equation (1) is achieved using the multiplicative coefficient $pA_i$:

$$\mathrm{pA_i} = \mathrm{A} \cdot \mathrm{A_i} \dots \mathrm{A_n}, \tag{2}$$

where A is the coefficient that depends on the quality of aggregates; $A_i$ are a coefficient, considering additional influence of i-th factor (i = 1…*n*) on concrete strength [12]. The influence of various factors on coefficient A was widely investigated [11, 12].

The coefficient A = $pA_i$ assumes that all factors $A_i$ are independent. Considering that the calculated strength values are only basic and are subject to experimental correction, this assumption can be accepted with a known accuracy range.

The usual technological information allows considering multiplicative coefficient, in addition to the main coefficient A, up to 2, 3 or more coefficients $A_i$.

The influence of the normal hardening duration can be approximately described by the well-known logarithmic dependence [2]:

$$\mathrm{A_\tau} = \lg n/\lg 28 = 0.69\lg n, \tag{3}$$

where *n* is the hardening duration in days.

The concrete strength calculation, subjected to heat treatment, has several features.The concrete strength calculation, subjected to heat treatment, has several features. Analysis of various experimental studies shows that the steamed concrete strength depends on the heat treatment parameters, the strength of cement during heat treatment and C/W.

The coefficients $A_i$ can be concretized by statistical processing of experimental data for a certain industrial enterprise. Table 1 presents an example of coefficients, characterizing effects on concrete compressive strength of: initial materials quality (A), hardening duration ($\mathrm{A_\tau}$), thermal treatment ($\mathrm{A_{\tau,t}}$), anti-freezing and hardening accelerating admixtures ($A_{ac}$), as well as calculated ($R_{cmp,c}$) and real ($R_{cmp,r}$) concrete strength values at C/W = 1.4 for Portland cement with the strength of 40 MPa.

**Table 1** Values of coefficients $A_i$, calculated ($R_{cmp.c}$) and real ($R_{cmp.r}$) concrete strength values ($R_{cem}$ = 40 MPa, C/W = 1.4)

| Concrete type | Hardening duration | Coefficients | | | | | $R_{cmp.c}$, MPa | $R_{cmp.r}$, MPa |
|---|---|---|---|---|---|---|---|---|
| | | A | $A_\tau$ | $A_{\tau,t}$ | $A_{ac}$ | pA | | |
| Normal hardening 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 steamed at 80°C, steam-curing cycle (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 | 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 real ones have not exceeded 17%. The strength of steamed cement ($R_{cem}^{st}$) can be expressed as:

$$R_{cem}^{st} = R_{cem} K_e, \quad (4)$$

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

The $K_e$ value varies from 0.55 to 0.75, depending on the features cement used.

Below are given graphs and corresponding regression equations (Figure 1) of the main efficiency coefficient $K_e^0$ depending on the isothermal heating duration $\tau_{is}$ and temperature $t_{t.t}$ for Portland cement and Portland Slag cement with the strength after steaming of 50 MPa ($K_{e_{p.c}}^0$) and 40 MPa ($K_{e_{s.p.c}}^0$) (respectively), obtained by the experimental data [13] processing.

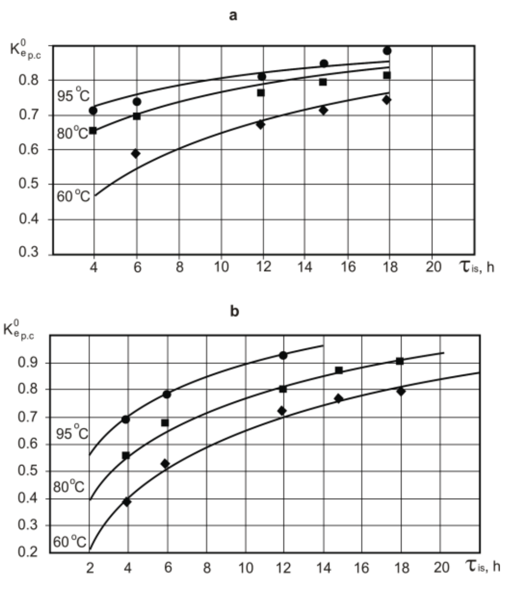


**Figure 1** Graphs for determining coefficients $K_e^0$: *a* - using Portland cement; *b* - using Portland Slag cement; ◊ - $t_{t.t}$ = 60°C; □- $t_{t.t}$ = 80°C; ○ - $t_{t.t}$ = 95°C.

The value of $K_e^0$ was found from the condition that $K_e^0 = R_{cem}^{st}/R_{cem}$. Approximating the experimental data (Table 2) the following equations were obtained:

$$K_{e_{p.c}}^0 = (0.3877 - 0.0032t_{t.t}) \ln \tau_{is} + 0.012t_{t.t} - 0.5096, \quad (5)$$

$$K_{e_{s.p.c}}^0 = (0.3693 - 0.0016t_{t.t}) \ln \tau_{is} + 0.0098t_{t.t} - 0.565. \quad (6)$$

**Table 2** Calculated and experimental values of $K_e^0$ and relative strength values.

| $K_e^0$ and relative strength values | Steaming temperature, °C, $t_{t.t}$ | Isothermal heating duration $\tau_{is}$, h. | | | | |
|---|---|---|---|---|---|---|
| | | 4 | 6 | 12 | 15 | 18 |
| Portland cement with tricalcium aluminate content $C_3A$ = 6…8% (authors data) | | | | | | |
| | 60 | 0.48 | 0.56 | 0.70 | 0.74 | 0.78 |
| Calculated values of $K_e^0$ | 80 | 0.63 | 0.69 | 0.78 | 0.81 | 0.83 |
| | 95 | 0.75 | 0.78 | 0.84 | 0.86 | 0.87 |
| | 60 | 0.51 | 0.59 | 0.67 | 0.72 | 0.75 |
| Experimental values of $K_e^0$ | 80 | 0.63 | 0.69 | 0.76 | 0.78 | 0.81 |
| | 95 | 0.71 | 0.74 | 0.81 | 0.86 | 0.89 |
| Slag Portland cement (authors data) | | | | | | |
| | 60 | 0.40 | 0.51 | 0.70 | 0.76 | 0.81 |
| Calculated values of $K_e^0$ | 80 | 0.55 | 0.65 | 0.82 | 0.87 | 0.92 |
| | 95 | 0.67 | 0.75 | 0.91 | 0.95 | - |
| | 60 | 0.39 | 0.52 | 0.71 | 0.76 | 0.8 |
| Experimental values of $K_e^0$ | 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% [13] | | | | | | |
| Experimental values for | 60 | 0.5 | 0.6 | 0.76 | 0.8 | 0.83 |
| relative strength of | 80 | 0.67 | 0.76 | 0.87 | 0.88 | 0.88 |
| concrete at W/C = 0.4 ($R_c^{st}/R_c^{28}$) | 100 | 0.70 | 0.72 | - | - | - |
| Slag Portland cement [13] | | | | | | |
| | 60 | 0.4 | 0.49 | 0.67 | 0.74 | 0.8 |
| Same | 80 | 0.55 | 0.64 | 0.84 | 0.9 | 0.92 |
| | 100 | 0.7 | 0.8 | - | - | - |

Table 3 shows the experimental and calculated values of $K_e^0$ obtained by Eq. (9, 10), as well as experimental values of $K_e^0$ obtained by Kayser [14] and the relative concrete strength $R_c^{st}/R_c^{28}$ at W/C = 0.4 following [13, 14]. $R_c^{st}$ is the compressive strength of steamed concrete, MPa; $R_c^{28}$ is the compressive strength of concrete hardened at 20°C at 28 days). An analysis of the calculated and experimental values of $K_e^0$ shows their high convergence (the average deviation of the $K_e^0$ values, calculated by Eq. (9, 10) from the experimental data is 5%).

**Table 3** 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 | (9) | 10.7 | 14.3 | 17.1 | 21.2 | 25.1 | 27.6 | 30.1 |
| | (11) K = 0.66; *b* = 0.74 | 10.6 | 13.9 | 16.6 | 20.5 | 24.5 | 27.1 | 29.8 |
| 25 | (9) | 12.1 | 16.2 | 19.4 | 24.1 | 28.7 | 31.6 | 34.5 |
| | (11) K = 0.66; *b* = 0.74 | 13.3 | 17.4 | 20.7 | 25.7 | 30.6 | 33.9 | 37.2 |
| 30 | (9) | 13.5 | 18.2 | 21.8 | 27.1 | 32.3 | 35.6 | 38.9 |
| | (11) K = 0.53; *b* = 0.74 | 12.9 | 16.9 | 20.1 | 25.0 | 29.8 | 33.0 | 36.2 |
| 40 | (9) | 16.4 | 22.0 | 26.5 | 33.0 | 39.4 | 43.6 | 47.7 |
| | (11) 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* were obtained by analyzing linear dependencies $R_c^{st}$ = *f*($R_{cem}^{st}$, C/W) following the data presented in [17].

The essential factors, affecting $K_e$, are the chemical-mineralogical composition, the mineral admixtures content and the cement strength:

$$K_e = K_A K_D K_{R_{cem}} K_e^0, \tag{7}$$

where $K_e^0$ is the main efficiency coefficient value that can be found from the Eq. (5, 6); $K_A$, $K_D$, $K_{Rcem}$ are correcting coefficients, depending on the aluminate content in cement, the mineral admixtures content and the steamed cement strength at 28 days.

Taking into account the data given in [14], for high aluminate cement at $\tau_{is}$ ≤ 3 h $K_A$ = 0.9; $\tau_{is}$ ≥ 6 h; $K_A$ = 0.8 for low aluminate cement at $\tau_{is}$ ≤ 3 h $K_A$ = 0.8; $\tau_{is}$ ≥ 6 h $K_A$ = 0.95; $\tau_{is}$ ≥ 9 h; $K_A$ = 1–1.1.

The $K_D$ coefficient value depends on the mineral admixtures' type and content. With content of the mineral admixtures is up to 10%, the strength of cement during steaming is usually constant. With a content of mineral admixtures of 20% a certain reduction of $R_{cem}^{st}$ is observed with shortened steam-curing cycles. At $\tau_{is}$ ≤ 4 h adding 20% of blast furnace slag and fly ash to cement cause an average strength decrease of 10% ($K_D$ = 0.9), pozzolana admixtures - 15% ($K_D$ = 0.85) [17]. At $\tau_{is}$ > 4 h - $K_D$ = 1.0.

For cement with 28-day strength of 50 MPa $K_{Rcem}$ = 1 [18], 40 MPa $K_{Rcem}$ = 1.05; 30 MPa $K_{Rcem}$ = 1.15; 55 MPa $K_{Rcem}$ = 0.95.

The steamed concrete strength at 28 days may be higher or lower than that of normally hardened concrete [13]. Researches and practical experience, show that with an optimal steam-curing cycle, strength loss can be minimized or eliminated as early as 28 days.

To obtain the C/W, providing the steamed concrete strength after 28 days, it is convenient to use the general equation for the concrete strength:

$$R_{cmp} = pA_i \cdot R_{cem}(C/W - 0.5). \quad (8)$$

According to the results of experimental data processing [13, 14], the coefficient ($A_1$) for steamed concrete with compressive strength $R_{cmp}^{28}$ up to 30 MPa equals 0.85–0.95, for $R_{cmp}^{28}$ > 30 MPa it is from 0.95 to 1.05. The lower values of $A_1$ are characteristic of shortened heat treatment cycles and concrete mixtures with high water demand. The value of the coefficient $A_2$ can be taken according to the well-known recommendations [13].

Kayser and Chekhova [14] investigated concrete strength variation after steaming. Based on the obtained experimental data the following equation was proposed:

$$R_c^{st} = 0.41(R_{cem}^{st} + 9)C/W - 0.83(C/W)^2 - 0.35R_{cem}^{st} - 7, \quad (9)$$

where $R_c^{st}$ is the concrete strength (MPa) 4 hours after the steaming cycle (2 + 3 + 6 + 2 at 80°C (for Slag Portland cement 90°C) using cement with strength of $R_{cem}^{st}$ (MPa), after steaming according to the same cycle.

Analysis of the experimental data [3] and Eq. (9), carried out by the authors, shows that for C/W ≤3 the linear dependence $R_c^{st} = f(C/W)$ is strictly enough complied (Table 3). Just at C/W >3, which is rather seldom in practice, an average correction for the nonlinearity of Eq. (9) can be applied:

$$\Delta R_c^{28} = 5(C/W - 3) \quad (10)$$

According to our data, for composition design it is rational to express the steamed concrete strength $R_c^{st}$ as well as $R_c^{28}$ using Bolomey formula:

$$R_c^{st} = pKR_{wtm}^{st}(C/W - b), \quad (11)$$

where $pK = KK_1K_2K_3 \ldots K_n$ is a multiplicative coefficient, considering the influence of various factors on steamed concrete strength (K is the basic coefficient, characterizing the effect of $R_{cem}^{st}$; $K_1$ – coefficient, depending on concrete mixture workability; $K_2$ – coefficient, taking into account the effect of steamed concrete aggregates features; $K_3$ – coefficient, considering strength growth due to hardening accelerators addition).

Using Eq. (11) for approximating the data, calculated according to Eq. (9), is acceptable (see Table 3). The values of basic coefficient K vary depending on $R_{cem}^{st}$ within the interval between 0.5 and 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 the deviation in the values of $R_{cem}^{st}$ calculated according to Eqs. (9) and (11) were below 10%.

Coefficient *b* in Eq. (11) varies insignificantly for the entire range of $R_c^{st}$ values (Table 3) and can be assumed to be equal to 0.74. Coefficient K decreases as the steamed cement strength increases (Table 3), which shows that the influence of the last on concrete strength has a certain nonlinearity. This conclusion also follows from Eq. (13).

The coefficient K, given in Table 3, are valid for low-slump concrete mixtures, based on crushed stone and medium-grained sand. Steamed concrete strength at C/W = const is significantly affected by water content and correspondingly workability, which can be taken into account in Eq. (15) by coefficient $K_1$. For concrete with slump Sl = 1 - 4 cm the value of $K_1$ = 1, and for those with Sl ≥ 9 cm - $K_1$ = 0.9, if Vebe time Vb = 30–50 sec then $K_1$ = 1.1 (Table 4).

**Table 4** 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 Eq. (15) 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 Eq. (15) at $K_1$ = 0.95 | 16.3 | 21.3 | 25.4 | 31.4 | 37.5 | 41.5 | 45.5 |
| $R_{cem}^{st} = 20$ MPa; Vb = 30-50 sec. | | | | | | | | |
| 5 | Experimental values | 10.5 | 14.8 | 17.7 | 23.5 | 27.6 | 28.5 | 31.1 |
| 6 | Calculated according to Eq. (15) at $K_1$ = 1.1 | 11.8 | 15.4 | 18.3 | 22.7 | 27.0 | 29.9 | 32.8 |
| $R_{cem}^{st} = 40$ MPa; Vb = 30-50 sec. | | | | | | | | |
| 7 | Experimental values | 17.4 | 23.8 | 29.8 | 35.7 | 42.8 | 48.8 | 52.1 |
| 8 | Calculated according to Eq. (15) at $K_1$ = 1.1 | 18.9 | 24.7 | 29.4 | 36.4 | 43.4 | 48.0 | 52.7 |

Notes: 1. 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 influence of the steamed concrete aggregate characteristics affects both through a change in water content and directly through a change in C/W, which is necessary to achieve the desired strength. In the last case a coefficient $K_2$ is added to Eq. (15). For regular 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 of clay, silt and dust content is rather high; $K_2$ = 0.9 for sand with fineness modulus below 1.5.

An essential reserve of necessary C/W reduction of steamed concrete can be provided by strong growth due to hardening accelerators, considered by coefficient $K_3$ in Eq. (11), and further hardening after thermal treatment.

The steamed concrete strength considering further hardening up to 1 day can be found in Eq. (12):

$$R_{c_1}^{st} = R_c^{st} + K_t I lg\left(\tau_{p.p}/\tau_{p.p}^0\right) R_c^{28}, \qquad (12)$$

where I is the concrete hardening intensity after the heat treatment; $\tau_{p.p}$ - post steaming period (0.5–24 h.); $\tau_{p.p}{}^0$ = 4 h.; $K_t$ - temperature coefficient (at an average temperature of concrete post steaming period 20°C – $K_t$ = 1.0; 30 – 40°C – $K_t$ = 1.1 – 1.2; 10°C – $K_t$ = 0.8, for concrete based on Slag Portland cement $K_t$ = 0.7); $R_c^{28}$ is the 28-day strength of normal hardening concrete.

Equation (13) for calculating / at $\tau_{p.p} \leq 1$ day, was obtained by the authors processing the experimental data [13]:

$$I = (0.000634R_c^{28} - 0.03254)\tau_{is} - 0.01R_c^{28} + 0.5787, \quad (13)$$

where $\tau_{is}$ is the isothermic heating duration, h.

For calculations according to Eq. (12), it is possible to use the nomogram presented in Figure 2.

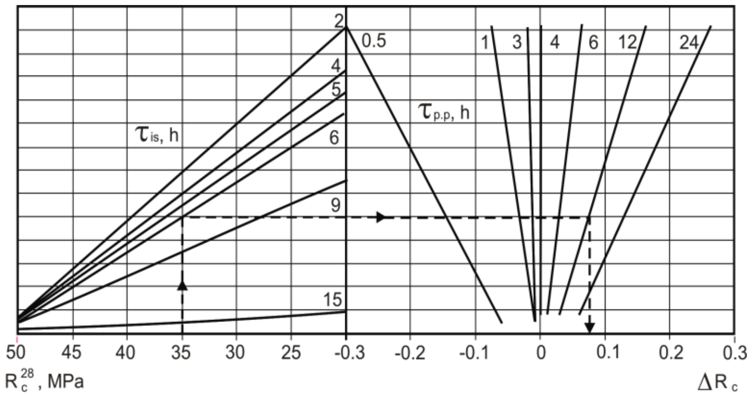


**Figure 2** Nomogram for calculating the increase in relative concrete strength $\Delta R_c = K_t I lg(\tau_{p.p}/\tau_{p.p}^0)$ after steaming and poststeaming period up to 1 day.

$A_t{}^{\tau_{p.p}}$ = 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:

$$R_{c_2}^{st} = R_{c_1}^{st} + K_t \frac{R_c^{28} - R_{c_1}^{st}}{lg28} lg\tau_{p.p}. \quad (14)$$

The proposed quantitative dependences enable the calculation of C/W for steamed concrete with given strength parameters at different temperatures and duration of hardening, taking into account the initial materials' properties and considering hardening after steaming (Table 5). It also allows quantitative estimation of different technological solutions to reduce cement consumption and heat energy.

**Table 5** Examples of calculating C/W and concrete thermal treatmentparameters.

| No. | Statement of the problem and initial data | Calculation scheme | Calculated and experimental results |
|---|---|---|---|
| 1 | Calculate C/W for manufacturing concrete with Vebe time Vb = 30…50 sec; $R_c^{28}$ = 20 MPa; $R_c^{st}$ = 17 MPa using Portland cement ($K_e$ = 0.65) with 28-day strength of 40 MPa, gravel and sand 4 h after steam-curing cycle (2 + 3 + 6 + 2 at 80°C). | Assuming A = 0.55; $A_1$ = 0.9; K = 0.66; $K_1$ = 1.1; $K_2$ = 0.95, and using Eqs. (8), (4) and (11) $(C/W)_1$, $R_{cem}^{st}$ and $(C/W)_2$ are calculated. The maximum C/W value is used for further calculations. | $(C/W)_1$ = 1.51; $(C/W)_2$ = 1.69; C/W = 1.69; $(C/W)_{exp}$ = 1.70 |

| | | | |
|---|---|---|---|
| 2 | Calculate C/W for manufacturing concrete with slump Sl = 5…9 cm; $R_c^{st}$ = 28 MPa; $R_c^{28}$ = 40 MPa using Portland cement with 28-day strength of 50 MPa (tricalcium aluminate content $C_3A$ = 7%, slag 20%), crushed stone and sand 8 h after steam-curing cycle (2 + 3 + 6 + 2 at 80°C) | Assuming A = 0.6; $A_1$ = 1; $K_1$ = 0.53; $K_2$ = 0.9; $K_A = K_D = K_{Rcem} = K_t$ = 1; $\tau_{p.p}^0$ = 4 h. and using Eqs. (8), (5), (7), (4), (13) $(C/W)_1$, $K_e^o$, $K_e$, $R_{cem}^{st}$ and I are calculated. After that $R_c^{st}$ is obtained from Eq. (12) and $(C/W)_2$. – from Eq. (11) The maximum C/W value is used for further calculations. | $(C/W)_1$ = 1.83; $K_e^o$ = 0.686; $K_e$ = 0.686; $R_{cem}^{st}$ = 34.3 MPa; I = 0.1356; $R_c^{st}$ = 24.7 MPa; $(C/W)_2$ = 2.25; C/W = 2.25; $(C/W)_{exp}$ = 2.23 |
| 3 | For C/W, obtained in example 2, determine the possible temperature decrease due to increasing the isothermal heating duration up to 9 h. and curing after steaming up to 24 h. | According to Eqs. (13), (12) and (11) calculate I, $R_c^{st}$ and $R_{cem}^{st}$. After that according to Eqs. (4) and (7) – $K_e^o$ and $K_e$, and from Eq. (5) $t_{t.t\,2}$, °C is found ($t_{t.t\,1}$ = 80°C). | I = 0.114; $R_c^{st}$ = 22.1 MPa; $R_{cem}^{st}$ = 30.6 MPa; $K_e^o$ = 0.61; $K_e$ = 0.61; $t_{t.t\,2}$ = 55°C; $\Delta t_{t.t} = t_{t.t\,1} - t_{t.t\,2}$ = = 80-55 = 25°; $\Delta t_{t.t\,exp}$ = 22°C |
| 4 | Find the possible decrease of C/W, obtained in example 2, due to increasing duration of curing after steaming up to 2 days at *t* = 20°C | From Eq. (14) obtain $R_{c1}^{st}$ and from Eq. (12) – $R_c^{st}$. After that from Eq. (11) find $(C/W)_x$ and compare it with $(C/W)_2$, obtained according to conditions given in example 2. | $R_{c1}^{st}$ = 24.8 MPa; $R_c^{st}$ = 22.1 MPa; $(C/W)_x$ = 2.09; ΔC/W = = $C/W_2 - (C/W)_x$ = = 2.25 – 2.09 = 0.16; $(\Delta C/W)_{exp}$ = 0.18 |

Calculating C/W for steamed concrete is expedient when it is complicated to obtain it experimentally or express composition design is necessary. For the wide application of this technique, it is desirable to accumulate experimental data obtained with various raw materials and heat treatment parameters.

## 4. Conclusions

1. The equations of 28 days and the tempering strength of steamed concrete are experimentally substantiated, allowing us to determine the required values of C/W, taking into account the steaming mode and the main technological factors.
2. To find the strength of cement developed under a given steaming regime, it is proposed to find the efficiency factor depending on the temperature and duration of isothermal heating of concrete.
3. Calculated dependencies are given, which make it possible to establish an increase in the strength of steamed concrete during subsequent hardening.
4. The obtained quantitative dependencies and recommendations make it possible to find the values of the required cement-water ratio for concrete that can be steamed under given

conditions. The cement-water ratio is the initial indicator for calculating concerete composition.

## Author Contributions

Conceptualization, V.Z. and L.D.; methodology, V.Z. and R.M.; software, V.Z. and R.M.; validation, V.Z. and R.M.; formal analysis, V.Z. and L.D.; investigation, V.Z.; resources, L.D.; data curation, V.Z.; writing—original draft preparation, V.Z. and L.D.; writing—review and editing, R.M.; visualization, V.Z.; supervision, L.D.; project administration, R.M.; funding acquisition, R.M.

## Competing Interests

The authors have declared that no competing interests exist.

## References

1. Neville AM. Properties of concrete. Krakow: Polish Cement Association; 2000. 874p.
2. Kosmatka SH, Wilson ML. Design and control of concrete mixtures. 15th ed. Skokie: Portland Cement Association; 2011. 460p.
3. Dvorkin O. Design of concrete compositions. (Basic theory and methodology). Rovno: NYVGP; 2003. 265p.
4. Liu B, Xie Y, Li J. Influence of steam curing on the compressive strength of concrete containing supplementary cementing materials. Cem Concr Res. 2005; 35: 994-998.
5. Nakajima N, Maruyama T, Koyama H, Date S. Effect of steam curing on initial strength development of mortar. Int J Eng Technol. 2017; 9: 468-473.
6. Hanif A, Kim Y, Usman M, Park C. Optimization of steam-curing regime for recycled aggregate concrete incorporating high early strength cement—A parametric study. Materials. 2018; 11: 2487-2501.
7. Gambhir ML. Concrete technology: Theory and practice. New Delhi: Tata McGraw Hill; 1986. p. 318.
8. Benammar B, Mezghiche B, Guettala S. Influence of atmospheric steam curing by solar energy on the compressive and flexural strength of concretes. Constr Build Mater. 2013; 49: 511-518.
9. Bingöl AF, Tohumcu İ. Effects of different curing regimes on the compressive strength properties of self compacting concrete incorporating fly ash and silica fume. Mater Des. 2013; 51: 12-18.
10. Ramezanianpour AA, Khazali MH, Vosoughi P. Effect of steam curing cycles on strength and durability of SCC: A case study in precast concrete. Constr Build Mater. 2013; 49: 807-813.
11. Dvorkin L, Dvorkin O. Basics of concrete science: Optimum design of concrete mixtures. Kindle edition. Saint-Peterburg: Stroi-Beton; 2006. 237p.
12. Sizov VP. Design of normal-weight concrete compositions. Moscow: Stroyizdat; 1980. 144p.
13. Mironov SA, Malinina LA. Accelerating concrete hardening. Moscow: Stroyizdat; 1964. 346p.
14. Kayser L, Chekhova R. Cements and their rational use in the production of prefabricated reinforced concrete elements. Moscow: Stroyizdat; 1972. 80p.
15. CEN. Methods of testing cement–Part 1: Determination of strength. Brussels: CEN; 2005; EN 196-1.

16. CEN. Testing hardened concrete-Part 1: Shape, dimensions and other requirements for specimens and moulds. Brussels: CEN; 2021; EN 12390-1:2021.
17. Desai PA. Effect of placing and curing temperatures on properties of concrete. Madison: University of Wisconsin--Madison; 1963. p. 112.
18. Ba MF, Qian CX, Guo XJ, Han XY. Effects of steam curing on strength and porous structure of concrete with low water/binder ratio. Constr Build Mater. 2011; 25: 123-128.