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A method for design of high strength concrete composition considering curing temperature and duration

L. Dvorkin [a], V. Zhitkovsky [a], Y. Stepasyuk [a], Y. Ribakov [b,*]

[a] Department of Building Elements, Technology and Materials Science, National University of Water and Environmental Engineering, Rivne 33028, Ukraine
[b] Department of Civil Engineering, Ariel University, Ariel 40700, Israel

HIGHLIGHTS

- HSC mix design considering curing temperature and duration is proposed.
- A method for predicting HSC strength after steaming and normal hardening is proposed.
- Good correlation between the calculated and experimental values was obtained.

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ABSTRACT

The paper deals with experimental results on temperature and curing duration influence on strength properties of high strength concrete (HSC). Dependences for calculating strength of high strength concrete at 12 h, 1, 7 and 28 days are developed for normal hardening conditions. Equations, allowing considering curing temperature in diapason between 5 and 40 °C as well as curing duration are proposed. The influence of steam curing parameters on HSC strength characteristics is investigated. Methodology for predicting concrete strength after steam curing and further normal hardening is proposed. The obtained calculation dependences and experimental-statistical models provide wide possibilities for design of effective high strength concrete compositions.

1. Introduction

High strength concrete (HSC) is widely used in modern construction. Mixtures with high workability and low water content are used for producing high performance concrete (HPC) classes C80 – C150 that have compressive strength of 30–50 MPa after two days of hardening [1]. HSC is a highly complex material, which makes modelling its behavior very difficult task [2]. Achieving desired properties of HSC is possible by using effective components for concrete mixture production, including admixtures, as well as proper design of optimal concrete mixture compositions [3].

Design methodologies of HSC composition are widely investigated [1,4]. Most of known methodologies are based on dependence of concrete strength on water-cement ratio [3,5]. Some researchers propose to design HSC compositions using experimentally obtained data for certain initial materials [6,7]. A methodology, considering maximal possible density of aggregates in concrete mixture and creating curves for dense mixtures was proposed [8]. Another well known methodology is selecting compositions of concrete, including HSC, by preparing mixtures in laboratory conditions and choosing the most economical solution, corresponding to the required strength parameters [6]. A method for self-compacting HSC composition proportioning was proposed [9]. It is based on solving complicated analytical equations that allow finding the required cement paste volume, providing the desired properties of concrete. Thus, most of the available methodologies require empirical selection of concrete parameters, considering certain factors.

Developing a design methodology, based on using experimental-statistical models that allow finding basic concrete mixture compositions that if required can be specified experimentally, is still an actual task. Considering curing temperature and duration in design dependencies that significantly affect the concrete strength [10] are of practical interest. Taking into account parameters of heat processing is especially important for precast concrete elements.

* Corresponding author.
E-mail address: ribakov@ariel.ac.il (Y. Ribakov).

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2. Analysis of available models for predicting HSC strength

According to classical theory [4], concrete strength at sufficient strength of coarse aggregate is proportional to the cement stone strength at equal other conditions. At equal cement stone strength the strength of concrete is higher for higher coarse aggregate modulus of elasticity (and correspondingly strength of its grains) as well as its bonding with the cement stone. In cases when the coarse aggregate strength is equal or higher than that of the cement stone and at proper bonding between them, the first has low effect on concrete strength.

Following Powers [11], compressive strength of cement stone specimens that hardened in normal conditions can be obtained at different ages using the empirical equation:

$$R_{c.s.} = AX^n \quad (1)$$

where A is a constant, characterizing the cement gel strength (A ≈ 240 MPa), n is a coefficient, depending on cement properties (n = 2.6–3); X is a structural criterion that characterizes the cement hydration products concentration in the space accessible for this substances (ratio between the gel and total volume of the gel and voids). The structural criterion can be calculated as

$$X = \frac{k_h V_{s.c}\alpha}{V_{s.c}\alpha + W/C} \approx \frac{0.647\alpha}{0.319\alpha + W/C} \quad (2)$$

where k_h = 2.09–2.2 is the hydration products volume growth coefficient; $V_{s.c}$ is the specific volume of cement ($V_{s.c} = 1/\rho_c = 0.319\ cb^3/g$); ρ_c is the cement density; α is the hydrated part of cement (hydration degree) and W/C is the water – cement ratio.

Similar equations, governing dependence of cement stone strength on its relative density were proposed also by other researchers [12–14]. Calculated values of cement stone strength according to Eq. (1) at different W/C and α are given in Table 1. Following the Table, at low W/C values there are more possibilities to increase the cement stone strength even at slight increase in cement hydration α. For example, if at W/C = 0.2 hydration degree α increases from 0.2 to 0.3, the cement stone strength is 73.8 MPa, whereas at W/C = 0.3 and α = 0.3 the calculated value of $R_{c.s}$ = 32.7 MPa, i.e. more than twice lower.

Experimental results [15] demonstrate higher cement stone strength growth at low W/C and rather slight increase in hydration degree. For example, at W/C = 0.2 increase in α from 0.1 to 0.2 yields cement stone compressive strength growth from 30 to 55 MPa and at W/C = 0.3 – just from 15 to 25 MPa. This is an important conclusion for developing proper technology of high strength ultra-rapid hardening concrete.

Influence of W/C, water to solid (W/S) and water-to-binder (W/B) ratios on HPC strength and durability at fresh and hardened states were studied [16]. For concrete mixture composition design, including HSC, it is more convenient to use the following equation:

Table 1
Effect of W/C and α on cement stone strength according to Eq. (1).

W/C	α	Cement stone compressive strength, MPa
0.2	0.2	32.7
	0.3	73.8
	0.5	178.6
0.25	0.2	20.1
	0.3	47.7
	0.5	124.0
0.3	0.2	13.3
	0.3	32.7
	0.5	89.8
	0.7	160.1
0.35	0.2	9.3
	0.3	23.4
	0.5	67.3
	0.7	124.0

$$f_c = AR_c(C/W - b) \quad (3)$$

where f_c is the required strength of concrete, R_c is the standard cement strength, C/W is the cement – water ratio that is used in this study in order to simplify the obtained equations, A and b are coefficients, considering properties of initial materials, concrete age and other technological factors. In this and other equations the required C/W or W/C are usually obtained for hardening in normal temperature conditions. Following available experimental data, obtained in the recent decades [17], the dependence between f_c and C/W is linear for C/W = 1–4. For average initial materials properties the results, obtained by Eq. (3), provide satisfactory agreement with experimental data, however in some cases the results are less accurate because many factors are not considered. The difference between experimental and calculated values can be 30–50% [17].

Attempts were made to use more complicated expressions for concrete strength [3,18], but as a result the main advantage – single dependence of f_c just on C/W – is lost. The prediction accuracy of Eq. (3) can be improved by refinement the expression and the coefficients based on experimental data for given conditions. In the last case the maximal effect is achieved by using mathematical planning methods [15] that allow obtaining experimental – statistical models in a form of regression equations that adequately describe the test results [20].

For prediction of the concrete strength growth in time an approximately linear relationship between strength f_c and logarithm of curing duration n ($n \geq 3$ days and t = 15–20 °C) can be used [1]:

$$f_n = f_{28}\frac{\lg n}{\lg 28} \quad (4)$$

where f_n and f_{28} are concrete strength values at n and 28 days, accordingly.

For concrete produced using modern cement the logarithmic dependence (4), usually underestimates the concrete strength at initial hardening stages (up to 28 days) and overestimates it after 28 days [1]. Eq. (4) was modified [21], considering two concrete strength values f_{n1} and f_{n2} corresponding to two hardening durations ($n1$ and $n2$):

$$f_n = f_{n_1} + \frac{\left(f_{n_2} - f_{n_1}\right)(\lg n - \lg n_1)}{\lg n_2 - \lg n_1} \quad (5)$$

Eq. (5) allows overcoming the drawback of Eq. (4), according to which the concrete strength at one day equals zero (lg 1 = 0). It also allows considering the influence of cement properties and other factors on concrete hardening rate.

For preliminary calculations of concrete strength vs. time more generalized empirical coefficients, differing for various cements, can be used [1]. Influence of temperature and hardening duration of concrete was studied by many researchers [1–2,4,11,14,22,23]. Analytical and graphical dependencies were proposed for estimating possible strength growth at different temperatures in humid conditions.

Concrete maturity concept was proposed for accessing efficiency of concrete hardening at different conditions [24]. This concept is based on a principle that concrete strength growth is a function of hardening duration and temperature. The method is described in ACI 306R-88 and ASTM C1074 [25,26] and can be used for accessing concrete strength growth. Following this concept, concrete hardening temperature and duration can be considered using two methods: simplified and more complicated. According to the simplified method, the factor, affecting concrete hardening rate, is called maturity factor, which is the product of hardening