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MAIN PRINCIPLES FOR SOLVING OF MULTI-PARAMETRIC CONCRETE COMPOSITION DESIGN PROBLEMS

ОСНОВНІ ПРИНЦИПИ ВИРІШЕННЯ ЗАДАЧ БАГАТОПАРАМЕТРИЧНОГО ПРОЕКТУВАННЯ СКЛАДІВ БЕТОНУ

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The article discusses the main approaches of the design methodology of concrete compositions taking into account the complex of specified parameters (multi-parameter design). The main types of problems arising in multi-parameter design are analyzed. A general algorithm is developed and examples of solving such problems are given.

У статті розглянуті основні підходи методології проектування складів бетону з урахуванням комплексу заданих параметрів (багатопараметричного проектування). Проаналізовано основні типи задач, що виникають при багатопараметричному проектуванні. Розроблений загальний алгоритм вирішення таких задач, що враховує багатоваріантність підходів до оптимізації складу бетону. Показані основні критерії оптимізації, що можуть бути застосовані при проектуванні складів бетону Наведені характерні приклади проектування бетону спеціальних видів, для яких необхідне одночасне забезпечення різних властивостей: міцності при стиску, розколюванні та при згині, повзучості, морозостійкості та водонепроникності та ін. Наведені основні теоретичні та емпіричні залежності, що пов'язують склад з основними параметрами бетонної суміші та бетону після його твердіння.

Key words: problems, optimization, properties, cement-water ratio, water consumption, strength.
Задачі, оптимізація, властивості, водоцементне відношення, водопотреба, міцність.

Multi-parametric concrete composition design (MPCCD) tasks differ from traditional by a big number of parameters considered at the “input” as well as an “output” of complex heterogeneous systems like concrete.

All MPCCD tasks can be divided into two types:

1. compositions problems, aimed at obtaining specific components consumptions, providing the given complex of concrete properties;
2. compositions - technological problems, aimed at finding along with specific components consumptions the values of some technological factors, characterizing the conditions of concrete producing and hardening.

Problems of both types are optimizatio ones and can be considered to be solved just if the formulated optimization conditions are satisfied [1-4].

Algorithms of compositions problems (Figure 1) suggest finding the basic parameters of the mixture - cement-water ratio (C/W), water consumption (W), entrained air volume (V_{air}) and portion of sand in the aggregates mix (*r*), providing the complex of given properties in the most effective manner. Algorithms of compositions - technological problems (Figure 1) suggest finding basic parameters of the mixture as well as technological process parameters $\left(\sum T_r\right)$ (temperature, hardening duration, compaction mode, etc.).

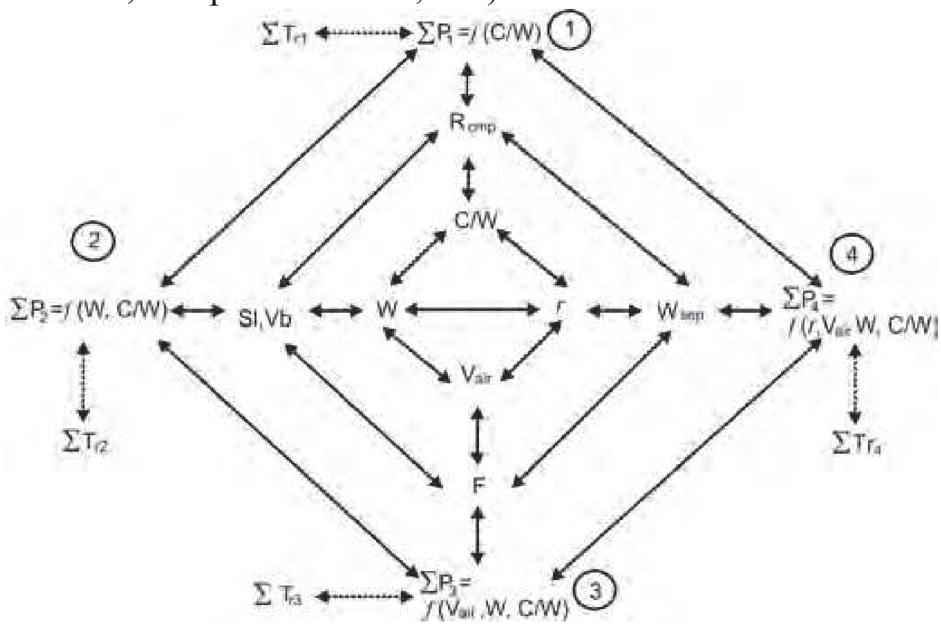

Figure 1. A block scheme for multiparametric concrete proportioning ($\sum P$ – a group of concrete properties, related to certain parameters of the mixture, $\sum T_r$ – a group of technological factors, affecting concrete properties).

Using basic mixture parameters together with equations of absolute volumes allows obtaining consumptions of a 5-component concrete mixture (cement (C), water (W), volume of entrained air (V_{air}), fine (S) and coarse aggregates (Cr.S).

The sequence of finding the mixture parameters is defined by the features of specific MPCCD tasks. Below possible schemes for obtaining C/W in problems with required compressive strength $\left(R^{rq}_{cmp}\right)$ and frost resistance $\left(F^{rq}\right)$ values are given as examples.

Problem A

Condition:

$$R_{cmp} = R^{rq}_{cmp}$$

$$F \geq F^{rq}$$

Without air entraining admixture

Solution:

$$\left.\begin{array}{l} 1.\ R^{rq}_{cmp} \rightarrow (C/W)_1 \\ 2.\ F \rightarrow (C/W)_2 \end{array}\right\rangle C/W$$

At $(C/W)_1 > (C/W)_2$ $C/W = (C/W)_1$

At $(C/W)_2 > (C/W)_1$ $C/W = (C/W)_2$

Problem B

Condition:

$$R_{cmp} = R^{rq}_{cmp}$$

$$F \geq F^{rq}$$

With air entraining admixture

(V^{rq}_{air} - required volume of entrained air)

Solution:

$$1.\ F \rightarrow V^{rq}_{air}$$

$$\text{at } R_{cmp} \geq R^{rq}_{cmp}$$

$$2.\ R^{rq}_{cmp} \rightarrow C/W$$

$$\text{at } V_{air} = V^{rq}_{air}$$

1. Obtaining R_{cmp} to achieve $\sum P_1 = f\,(C/W)$ and required C/W.

2. Obtaining the water consumption W for achieving $\sum P_2 = f\,(W, C/W)$. Sl and Vb are Slump and Vebe time values, accordingly.

3. Obtaining the entrained air volume V_{air} for achieving $\sum P_3 = f\,(V_{air}, W, C/W)$.

4. Obtaining parameter r for achieving $\sum P_4 = f\,(r, V_{air}, W, C/W)$. W_{sep} is the water separation value.

Realization of the above presented algorithms is possible due to unequivocal relation between the group of the major physical-mechanical properties of concrete and C/W. This group of properties includes first of all strength parameters, a number of deformation and other properties, determined by the ratio of hydrated cement volume and concrete porosity. For MPCCD tasks the W/C rule should be considered as a basic regularity, determining the entire complex of the above mentioned properties, and not just compressive strength.

For concrete with admixtures and lightweight concrete it is expediently to use as the core composition parameter the "modified C/W". It essentially increases the applicability range of design-experimental methods of concrete proportioning and dependencies for calculating concrete strength.

Selecting quantitative dependencies should consider as the purpose of a specific problem, as available initial information. For example, in simple problems, including finding strength of regular concrete without mineral, air entraining or other admixtures in normal hardening conditions the most known formulas may be used [5]. If detailed information regarding initial materials features is available, coefficients in equations of concrete strength are specified according to appropriate recommendations [6, 7].

Various quantitative dependences can be used also for obtaining aggregates consumption. At known aggregates specific surface and voidage values it is possible to use a formula, proposed in [8], to obtain the optimal portion of sand in aggregates mix (r_{opt}). In cases, when along with cement consumption and W/C just water demand of sand is known, the crushed stone consumption can be obtained by calculating the moving apart coefficient of coarse aggregate's grains by the cement-sand mortar K_s according to recommendations [6, 7]. If voidage of sand and crushed stone are known (these parameters can be easy found if true and bulk densities of aggregates are known) calculation of K_s can be done using dependencies given in [7] with corresponding corrections. The bank of quantitative dependences available in concrete science rapidly increases during the last years especially due to polynomial regression equations – adequate mathematical models in a defined "factorial space". The major part of these models is obtained by means of experiment planning methods.

A characteristic feature of MPCCD tasks algorithms is considering the intervals of possible mixture parameters values, caused by various normed factors.

Such interval is characteristic, for example, for C/W at norming various strength parameters (Figure 2). Similarly, "scissors" by water consumption form, for example, concrete mixture workability and shrinkage parameters (Figure 3), by the entrained air volume - strength and frost resistance (Figure 4). It requires including in MPCCD tasks algorithms special calculations, related with obtaining values of such mixture parameters, which would provide the entire complex of normed properties. In each group of properties one of the factors becomes dominant. Achieving this factor assumes at the same time achieving other normed parameters in the same group. For example, following Figure 2, if $R_{cmp} \geq 20$ MPa, $R_{t.b} \geq 8.3$ MPa, $R_{s.t} \geq 7.9$ MPa are normed, than it is evident that $R_{s.t}$ is a dominant parameter and the required C/W, providing the three properties, equals 2.1.

To calculate mixture parameters it is possible to use equations that are directly related to these parameters, or expressions, considering the parameters indirectly. Formulas of the first type are more preferred, as for them mistakes, caused by correlation level of interrelated parameters (for example, between tensile strengthand compressive strength and others) are not characteristic.

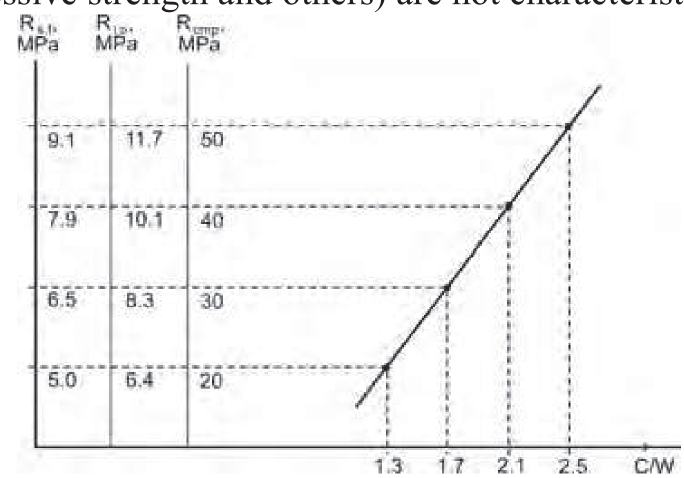

Figure 2. Affect of C/W on compressive strength (R_{cmp}), tensile bending strength ($R_{t.b}$) and splitting tensile strength ($R_{s.t}$).

Note: The graphs were obtained using known design formulas [5, 9].

Not all dependences recommended for calculation of $P_i = f(R_{cmp})$, where P_i is the concrete property indicator, are enough unequivocal. Some researchers [10, 11], for example, propose to relate the creep value (C_m) just with concrete compressive strength. At the same time the essential influence of cement stone content on C_m at R_{cmp} = const is presently considered to be proved (Figure 5). It is in agreement with physical hypotheses about the mechanism of concrete deformations at long term load action [11, 12]. It was also shown that cement stone content along with compressive strength in a wide compositions range has an essential influence on concrete elasticity modulus [10]. As known, the European Concrete Committee recommends to use for estimating elasticity modulus dependences, relating it just with compressive strength [10].

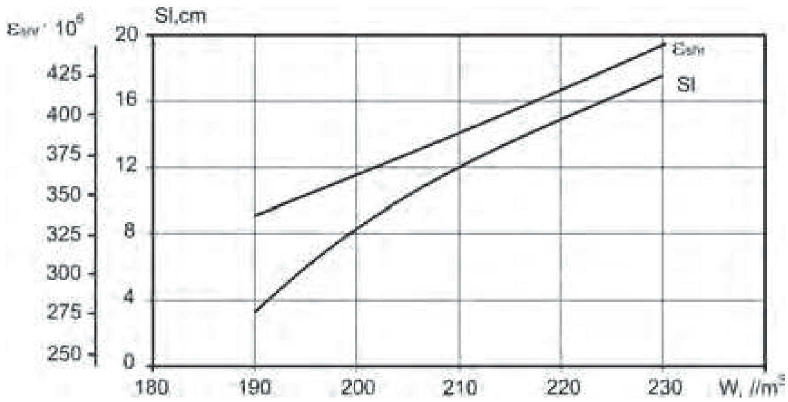

Figure 3. Dependence between water content (W), concrete mixture slump (Sl) and concrete shrinkage (ε_{shr}).

Note: Dependence between Sl and W is taken according to [7] for regular materials; concrete shrinkage was calculated using the following formula [10]: $\varepsilon_{shr} 10^6 = 0.125 W \sqrt{W}$.

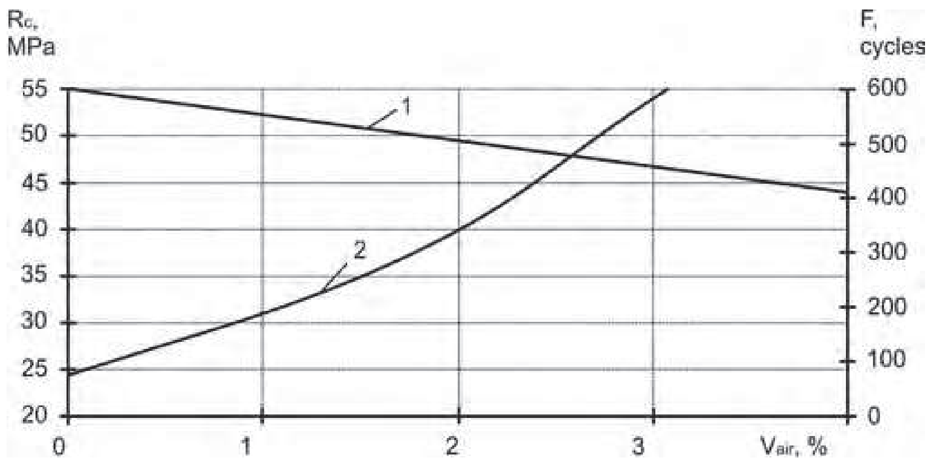

Figure 4. Dependence between the entrained air volume, concrete strength (R_c) (*1*) and frost resistance (F) (2).

Note: concrete strength is calculated for regular materials using a formula $R_c = AR_{cem}\left(\frac{C}{W+V_{air}} - 0.5\right)$ (where A is a coefficient depending on initial materials quality), concrete frost resistance is obtained for regular materials according [9].

It is also possible to show ambiguity of concrete compressive strength dependences and correspondingly C/W or W/C on group of properties, determined by capillary porosity (water absorption, frost resistance, etc.). As known, [13, 14], capillary porosity (P_{cap}) of concrete can be obtained as:

$$P_{cap} = \frac{W - W_t \alpha C}{1000} \tag{6.1}$$

where W_t is the quantity of chemically related water; α - cement hydration degree.

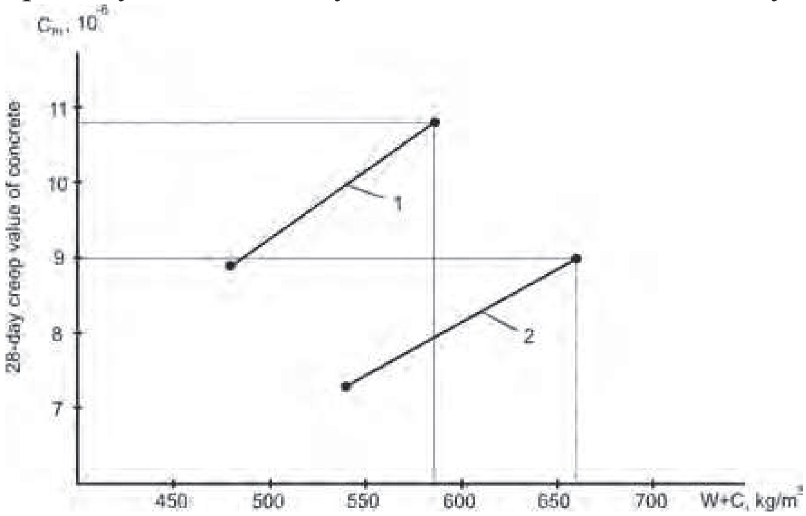

Figure 5. Effect of cement stone content in concrete on creep value:
1 – R_{cmp} = 20 MPa; 2 – R_{cmp} = 30 MPa.
Note: Creep value (C_m) is calculated according to [9].

Dependences of the considered type can be used for checking the possibility of achieving corresponding properties indicators at known compositionand correction the mixture parameters. For example, if the average concrete strength is given R_{cmp} = 65 MPa and the creep value $C_m \cdot 10^6 = 3.5$. Slump of concrete mixture, produced using crushed granite stone and medium-fineness sand, is Sl = 2cm. Cement strength R_{cem} = 50 MPa. Using formula $R_{cmp} = AR_{cem}(C/W - 0.5)$ if A = 0.6 than C/W = 2.63. The required concrete mixture slump is provided at water consumption W = 175 l/m³.

For checking the possibility of achieving the given value of creep it is possible to use the formula, recommended by the European Concrete Committee [10]:

$$C_{m(28)} = \frac{K \cdot \mathrm{W}/C \ \ (W + 0.33C)}{\sqrt{10R_{cmp}}} \tag{6.2}$$

where К is a coefficient, depending on the element's section dimensions and the surrounding environment humidity.

At W = 175 l/m^3, W/C = 0.38, C = 460 kg/m^3, R_{cmp} = 65 MPa and К = $0.92 \cdot 10^{-6}$ $C_m \cdot 10^6 = 4.5$. For achieving the given value of $C_m \cdot 10^6$ it is required to decrease the W/C or consumptions of water and correspondingly cement.

In certain multi-parametric problems providing a complex of given properties is impossible without special technological solutions like using admixtures, temperature regulation, etc. For example, such technological solutions are required for providing high concrete mixture slump and low shrinkage, decreasing heat generation at high strength, etc. The problem becomes even more complicated if technological parameters (temperature, hardening duration, type of falsework, etc.) are also limited.

Table 1 presents examples of multi-parametric concrete composition design (MPCCD) tasks solutions, illustrating the above mentioned statements.

Optimization of concrete mixtures compositions in MPCCD tasks suggests narrowing the intervals of mixture parameters and decreasing the required C/W and W values. The optimization solution selection is carried out considering specific possibilities and limitations and aimed at achieving the required optimization conditions. The most effective are technological solutions, directed on achieving a complex effect. In particular, at solving optimization MPCCD tasks it is effective to use admixtures like polyfunctional modifiers (PFM). PFM can be represented by single or composite admixtures of different types.

For composition-technological problems optimization of composition is achieved by selecting the best mixture parameters at the most rational values of regulated technological factors.

Table 1.

Examples of obtaining cement water ratio (C/W) and water consumption (W) in MPCCD tasks

<table>
<tr><td colspan="2">Obtain the required C/W for producing concrete using regular materials (R_{cem} = 50 MPa):
1) with compressive strength at 28 days R_{cmp} = 30 MPa and tensile bending strength $R_{t.b}$ = 4 MPa</td></tr>
<tr><td>Main design formulas:
$R_{cmp} = 0.4 \cdot K \cdot R_{cem} \cdot C/W$
(К = 0.95 [9])
$R_{t.b} = 0.08(10R_{cmp})^{2/3}$</td><td>Calculated C/W:
C/W_{Rcmp} = 1.58
$C/W_{Rt.b}$ = 1.86</td></tr>
<tr><td colspan="2">$C/W_{Rt.b} > C/W_{Rcmp}$</td></tr>
<tr><td colspan="2">2) with compressive strength at 28 days R_{cmp} = 30 MPa and heat generation Q = 68000 kJ (W = 190 l/m^3)</td></tr>
</table>

Main design formulas: $R_{cmp} = 0.4 \cdot К \cdot R_{cem} \cdot C/W$ (К = 0.95 [9]) $Q = g_7 C$ $g_7 = 26.15 R_{cem}^{2/3}$	Calculated C/W: $C/W_{Rcmp} = 1.58$ $C/W_Q = 1.01$
$C/W_{Rcmp} > C/W_Q$	
3) with slump of concreteной mixture Sl = 20 cm (W = 220 l/m^3) and shrinkage $\varepsilon_{shr} = 0.3$ mm/m	
Main design formulas: $\varepsilon_{shr} \cdot 10^6 = 0.125 W \sqrt{W}$ $W = f(Sl)$ [9] (data from graphs and tables)	Calculated water consumption: $W_{Sl} = 220\ l/m^3$ $W_{shr} = 179\ l/m^3$
$W_{Sl} > W_{shr}$	

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