Strength and deformations of high-strength concrete under short-term heating conditions up to +90°C

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Abstract. The results of experimental researches of short-term heating effect up to +90°C on strength, modulus of elasticity and ultimate strains under axial compression of modified high-strength concrete of C70÷C90 classes were presented. The concrete was obtained with the modifier application MB10-50C. Temperatures of tests – +20°C; +50°C; +70°C; +90°C. Lifting speed of temperature during heating – 15°C/h. The decrease of concrete strength under axial compression was installed in short-term heating conditions up to +50°C; +70°C; +90°C respectively 20%, 23%, 28% by comparison with tests at the normal temperature. Meanwhile, the modulus of elasticity decreased 18%, 20% and 22% respectively. The ultimate compressive strain of concrete increased 15%, 9%, 11% respectively at the same temperatures. This work was carried out within the frameworks of the grant of FNI Ministry of construction of Russia and RAASN on the topic 7.4.15-18 «Fundamental scientific researches of the elevated temperatures’ influence up to 200°C on the characteristics of physical-mechanical and rheological properties of modified high-strength concrete of C70÷C90 classes».

1. Introduction

Most of the buildings and structures during construction and exploitation are subjected by repeated short-term, long-term, variable loads and the effect of elevated technological temperatures. Thermal effects are usually set as temperature gradients, cause heterogeneity of material properties and have a significant impact on the stress-strain state of structures [1,2]. The stress-strain state of structures of such objects depends on a large extent of temperature influences and associated with strength and deformations. As a result, development and application of new and effective materials in construction and reinforcement of concrete structures become particularly important. The results of the experimental research of high-strength concrete prove that the first short-term heating of structures is the most dangerous. This type of impact is characterized by the greatest decrease (up to 20%) in the strength and modulus of elasticity of concrete under axial compression and an increase of ultimate compressive strain about 11% [1,3,4]. Such changes in the mechanical properties of concrete in combination with thermal deformations and creep of concrete significantly adjust the stress-strain state of concrete structures. The main factors that affect the change in the properties of concrete are structural stresses at the contact "cement stone – aggregate", as well as additional vapor pressure in the pores during the evaporation of chemically unbounded water [1,3].

Modified concretes based on organic-mineral modifiers [5,6] that supply concrete with additional properties and guarantee high exploitative reliability of structures have recently become widely used...
in construction. Such concretes have high (60-80 MPa) and super high (more than 80 MPa) strength, and are characterized by high flow of concrete mix, low permeability, higher corrosion resistance and durability [5,7,8].

In Russian design code 27.13330.2017 [9], strength and deformation of structures are provided for two main cases of their works: short-term heating and long-term heating. Meantime, their temperature deformations and characteristics of mechanical properties under short-term heating conditions up to +90°C in respect of modern high-strength concretes are still insufficiently studied. The purpose of this research is to obtain the characteristics of strength and deformations of modified high-strength concretes of classes up to C90 for a range of elevated temperatures and to develop recommendations for taking into account the effect of short-term heating up to +90°C on the physical and mechanical properties of high-strength concrete.

2. Methods

2.1. Materials

Thermal strains and mechanical properties of modified high-strength concrete were studied at normal (20°C) and elevated to +90°C temperatures. Concrete consisted of a mixture of cement: sand: water = 1:1.61: 0.29 with a modifier [5,10] in the amount around 20% of the cement weight. Coarseness modulus of sand was 2.1÷2.5 mm. Details of the mix proportions are given in table 1. Concrete mix was characterized by high mobility (slump = 25 cm). The test specimens are cubes with edges of 100 mm and prisms had the dimensions of 100×100×400 mm. Storage conditions were the following: temperature \( t = 20 \pm 2°C \) and relative humidity \( W = 90 \pm 10\% \). Compressive prism strength \( f_c \) and the modulus of elasticity \( E_c \) of high-strength concrete at the age of 28 days at normal temperature were respectively 61.39 MPa and 38.47×10\(^3\) MPa.

Table 1. Material consumption per 1 m\(^3\) of concrete mix.

| Components of the concrete mix, kg/m\(^3\) | Unit weight, kg/m\(^3\) | W/C | W/(C+MB) | S(C+MB) |
|------------------------------------------|------------------------|-----|-----------|---------|
| Cement: Portland PC500D0;                | 490                    | 2398| 0.34      | 0.28    | 1.34
| Sand with coarseness modulus: 2.1÷2.5 mm;| 790                    |     |           |         |
| Aggregate: granite fractions 5÷20 mm;    | 850                    |     |           |         |
| Water;                                   | 168                    |     |           |         |
| Organic-mineral modifier MB10-50C consisting of MB 20% of cement weight. |

2.2. Testing

Heating of specimens was carried out in a special constructed heating apparatus consisting of three layers of special thermal-resistant asbestos fabric and comprising a planar coil of nichrome wire. The heating temperature set was maintained by the corresponding electrical voltage in the coil with the help of the voltage regulator. The control of heating temperature was done by the indications of chromel-copel thermocouples. Linear lengthwise strains of specimens were measured with the indicating gages. The gage length of lengthwise strains on prisms with the height of 400 mm was 250 mm. The duration of short-term heating before press loadings at 50°C, 70°C and 90°C was 18, 16 and 15 hours respectively, which corresponded to the time of minimum strength achievement by high-strength concrete under the same test temperature [1,10]. The temperature rise speed during heating was 15°C per hour. The loading was carried out in stages with a step of 0.1 from the expected ultimate breaking load with a 5-minute hold at each stage. The characteristics of concrete deformation properties (modulus of elasticity \( E_c \)) were determined according to the standard method at the loading level \( \eta = \sigma_c / f_c \leq 0.3 \), ultimate compressive strain at the peak stress \( \varepsilon_c \) – according to the values corresponding to the maximum level of stress achievement in the experiments.
3. Results and Discussion

3.1. Influence of age on the mechanical properties of high-strength concrete

Press tests were carried out in the Research and Testing Laboratory of Building Structures and Materials "Polytech-Skim-Test" at the age of 7, 28, 53, 114, and 142 days. The average values of the cubic strength $f'_c$ of concrete at the age of 28 days were on average from 92÷95 MPa, which corresponds to the class of concrete at axial compression C90÷C100. The increase of strength at the age of 53, 114, and 142 days was respectively 15%, 16%, and 17% in relation to the strength at the age of 28 days. Experimental data indicates about the most intensive strength gain of modified high-strength concrete up to 70% in the first 7 days and up to 90% at the age of 28 days, as well as about a significant decrease in the growth rate after 28 days of age (Figure 1a), which quite well correlates with researching results by the other authors [11].

![Figure 1](image-url)

**Figure 1.** Influence of age at normal temperature $+20\degree C$ on the relative strength (a), modulus of elasticity (b), stress-strain diagram (c) and ultimate compressive strain (d) of high-strength concrete.

1 – by Korsun V.I., Khon Khemarak; 2 – by Korsun V.I., Ha V.K.; 3 – by Mohd Zain M.F., Radin S.S.[4] 4 – calculation by Skramtai B.G. [14] 5 – calculation by Sherbakov E.N. [15] 6 – calculation by Mishina A.V. [15]
The value of modulus of elasticity on average at the age of 28 days is $3.847 \times 10^3$ MPa, and for specimens at the age of 142 days – $29.02 \times 10^3$ MPa (Figure 1b), which indicates that the aging of concrete leads to a decrease $E_c$ on average 25% at the age of 142 days compared to values at the age of 28 days.

The ultimate compressive strain under axial compression at the age of 142 days was $3.19 \times 10^{-3}$ (Figure 1d), which was 7% higher than specimens aged 28 days. The loading levels corresponding to the practical elastic deformation of concrete do not depend on the age of the concrete and are in the range of $0.7\cdot f_c'$. The process of elastic reduction of the high-strength concrete volume was replaced by dilation at loading levels higher $0.9f_c'$. The levels of cracking were at the same level as for specimens aged 28 days [12].

The theoretical description of changes [13] in the strength, modulus of elasticity and the ultimate compressive strain according to the time was carried out by the methods of different authors (Table 2).

**Table 2. Description of the changes in time of physical and mechanical properties of high-strength concrete.**

| Author         | Expression                                                                 |
|---------------|---------------------------------------------------------------------------|
| Skramtai B.G. | $f_{,cT} = f_{,cT}' \cdot \frac{\lg T}{\lg 28} = 0.7 \cdot f_{,cT}' \cdot \lg T$; (1) |
| Berg O.Ya.    | $f_{,cT} = \frac{1000 - \tau}{5 \cdot (100 + f_{,cT}')} \cdot \frac{\lg 28}{\tau}$; (2) |
| Sherbakov E.N | $f_c(T) = f_c(28) \cdot \left[1 + \frac{28}{55 + c} \cdot \left(\frac{T - 28}{T + 5}\right)\right]$; (3) |
|               | $E_c(T) = E_c(28) \cdot \left[1 + \frac{28}{55 + c} \cdot \left(\frac{T - 28}{T + 5}\right)\right]^{0.3}$; (4) |
| Mishina A.V.  | $f_c(T) = f_c(28) \cdot \frac{T}{2.3 + 0.92T}$; (5) |
|               | $E_c(T) = E_c(28) \cdot \left(\frac{T}{2.3 + 0.92T}\right)^{0.4}$; (6) |

where $f_{,cT}$ – temporary resistance to compression of concrete cube at the age of $T$, day; 
$f_{,cT}'$ – the same, at the age of 28 days, MPa;

$f_{,cT}'$ – cubic strength of concrete at the age $3 \leq \tau \leq 180$ days;

$f_c'$ – cubic strength of concrete at age of 28 days, MPa;

$c$ – class of concrete on compressive strength, MPa;

$T$ – age of concrete at the time of testing, day.
By the comparative results of experimental and theoretical data, it was found that the logarithmic expressions (1) and (2) incorrectly describe the strength growth for modified high-strength concrete, while the proposed expressions for the other methods (3) and (5) describe well enough results of researches with an average deviation around 7÷9%.

3.2. Short-term heating influence of high-strength concrete on the mechanical properties under axial compression

The decrease in prismatic strength of modified high-strength concrete [8,17] under axial compression of short-term heating was respectively 20%, 23%, 28% at temperatures +50°C, +70°C, +90°C compared to the strength values at normal temperature (Figure 2a), modulus of elasticity – 18%, 20%, 22% (Figure 2b), ultimate compressive strain increased 15%, 9%, 11% (Figure 2d).

The deformation curves [18,19] of high-strength concrete under axial compression in the temperature range from 50°C to 90°C are shown in Figure 2c. The loading levels corresponding to the practical elastic deformation of concrete in researching temperature range were almost 0.8 of the cubic strengths. The process of elastic reduction of high-strength concrete volume specimens changed by its increase (the effect of dilatation) at loading levels above 0.9 $f_c'(t)$.

The changes in strength and strain [7] properties of concretes exposed to elevated temperatures are caused by the manifestation of destructive and constructive factors in the concrete structures. The most significant destructive factors are structural stresses in the contact zone “matrix–aggregate” which in most cases become evident during the first heating of fine concretes.

Figure 2. Short-term heating influence on the changes of relative strength $\gamma = f_{c,tem} / f_c$ (a), modulus of elasticity $\beta = E_{c,tem} / E_c$ (b), stress-strain diagram (c) and ultimate compressive strain $\varepsilon_{c,tem} / \varepsilon_c$ (d) concrete under axial compression.
4. Conclusions
Experimental researches of the influence of age on physical and mechanical properties of modified high-strength concrete at normal temperature of +20°C have been carried out. The strength, modulus of elasticity and ultimate compressive strain according to the age of high-strength concrete has exactly been established by the experiments: aging of concrete led to increase the strength at the age of 142 days about 17%, modulus of elasticity decreased around 25% and ultimate compressive strains under axial compression increased by 7% compared to the corresponding values at the age of 28 days. The theoretical description of changes in strength and modulus of elasticity according to the time have been performed by using formulas (1÷5) (table 2). Experimental researches of strength, modulus of elasticity and ultimate compressive strain depend on the temperature and heating duration. The strength of high-strength concrete under short-term heating in the temperature range from +20°C to +90°C is reduced an average around 23%, modulus of elasticity about 20% and ultimate compressive strain during axial compression of concrete at the same temperatures increases 11% compared to the corresponding characteristics at normal temperature. The recommended codes [9,20] for accounting of the elevated temperatures influence on mechanical properties of normal strength concrete can also be applied to modified high-strength concretes.

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