The calculation of creep deformation of high-strength concrete in relation to the conditions of exposure to elevated temperatures

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Abstract. The results of generalization and analysis of experimental research data on the creep deformation of heavy concretes of medium and high strength under conditions of elevated temperatures up to +200°C are presented. It is shown that the experimental data of some authors are difficult to compare due to the significant influence of differences in test methods. All other things being equal, modern high-strength modified concrete is characterized by lower creep deformations in comparison with ordinary medium-strength concrete. It is shown that the ultimate values of the specific creep deformation of high-strength concrete at a long compression level of $\eta = 0.5$ under conditions of heating to 200°C are lower, on average, by 45% in comparison with similar characteristics for ordinary concrete of medium strength. With an increase in the level of long-term compression from $\eta = 0.2$ to $\eta = 0.5$, the specific creep strain of ordinary concrete of medium strength increases in the temperature range from +20°C to +200°C on average, by 28%, and in high-strength concrete with an increase in the level of long-term compression with $\eta = 0.3$ to $\eta = 0.6$, an increase in the similar characteristic was about 40%. The specific creep strain of high-strength concrete at a long compression level of $\eta = 0.5$ with an increase in the heating temperature from +20°C to +200°C increases by 2.8 times, and for medium-strength concrete – by 3.1 times. The massiveness of the samples (scale factor) can be taken into account using a parameter such as the modulus of the open surface. With an increase in the modulus of the open surface with a decrease in the mass of the samples, the creep strains of high-strength concrete increase at all heating temperatures. In relation to simplified engineering calculation methods, the recommended values of creep coefficients for concrete of classes B60 – B90 are proposed. In the development of concrete deformation models, approximating expressions have been developed that allow reliably assessing the creep strains of high-strength concrete of classes up to B90. The method relationships are based on the theory of aging and take into account the influence of the heating temperature, the duration of its action, the influence of the nonlinear component of creep, and the scale factor. The temperature and duration of heating before and after application of the load are taken into account using the functions of the reduced time. Satisfactory compliance of the calculated values of creep deformation of high-strength concrete with experimental data is shown.

1. Introduction

Reinforced concrete structures of a number of industrial buildings and engineering structures during operation are subjected to combined power and temperature effects of various durations. Creep deformations of concrete at elevated temperatures can exceed the corresponding deformations at...
normal temperature by 2–3 times [1–6]. In combination with temperature-shrinkage deformations, creep of concrete is an essential factor determining the SSS of structures at all characteristic stages of their life cycle: the first short-term heating, long-term heating, and cooling after long-term heating [1–6].

Modern high-strength modified concretes [7] can be especially effective for structures of industrial buildings and engineering structures exposed to high technological temperatures [1–6]. However, the widespread use of high-strength concrete for structures of these types is constrained by the lack of reliable methods for calculating their temperature-shrinkage deformations and creep. In the current Russian code of rules SP 27.13330.2017 [6], there is no data on the effect of elevated temperatures on the characteristics of the physicomechanical and rheological properties of concrete of classes higher than B60 due to insufficient knowledge. Well-known engineering methods for calculating temperature-shrinkage deformations and creep [1, 2, 6, 8–11] are developed for medium-strength concrete and require their refinement in relation to high-strength concrete.

Studies of concrete creep deformations were carried out both by a number of domestic [1–11] and foreign authors [12–20]. In SP 27.13330.2017 [6], creep deformations of concrete under heating conditions can be taken into account by adjusting the concrete deformation modulus using the creep coefficient \( \phi_{b,cr} \), normalized only for concrete of strength classes no higher than B60. For concrete of higher classes, this characteristic is not standardized due to its insufficient study.

For deformation models that are currently being actively developed, it is preferable to analytically represent the dependence of the creep strain of concrete on the main factors of influence: on the values of concrete age at the beginning of loading \( \tau_0 \) and at the beginning of heating \( \tau_t \), on the level of long-term loading \( \eta_\sigma \), on the heating temperature \( t_0 \) and duration its actions \( T \), from the regimes of temperature and force effects and from other factors. For concretes of medium strength classes (B25 ÷ B35), such relations based on the theory of aging were developed in [1].

The purpose of this study is to generalize and analyze experimental data for concrete of high strength classes (B60 ÷ B90) with the development of an appropriate methodology and approximating expressions for calculating creep deformations as applied to conditions of exposure to temperatures elevated to +200°C.

2. Methods

In the current norms of SP 27.13330.2017 [6], creep deformations of concrete are taken into account using the creep coefficient \( \phi_{b,cr} \), defined as the ratio of the total creep deformations of concrete under prolonged exposure to temperature and the elastic deformations of concrete before exposure to temperature.

Based on the analysis of the experimental data presented in Fig. 1 [3, 4], the recommended values of the creep coefficient \( \phi_{b,cr} \) are presented in table 1.

| Concrete strength classes | Values of concrete creep coefficients \( \phi_{b,cr} \) with prolonged heating, °C |
|--------------------------|-----------------------------------------------|
| B25 – B60                | 3.35 70 100 200 |
| B70 – B90                | 2.5 6.2 7.8 8.7 |

Note: the values for concrete B25 – B60 are accepted according to SP 27.13330.2017 [6]

To analytically describe the creep deformations of high-strength modified concrete of classes B60 – B90 under the influence of elevated temperatures, the following approximating expressions have been developed, constructed by analogy with the method [1].

The creep strain of concrete \( \varepsilon_c \) under conditions of prolonged exposure to compressive stress \( \sigma \) and elevated temperature to at time \( T \) is determined by the formula:

\[
\varepsilon_c = (\ell', T_{red}, \tau_{red}, \eta_\sigma) = C(\ell', T_{red}, \tau_{red}, \eta_\sigma) \cdot \sigma.
\] (1)
The total specific creep strain of concrete, taking into account the nonlinear component at elevated temperatures:

\[ C(\sigma,t,\tau_{\text{red}},M_0) = (1+\Delta f(\eta_\sigma t)) \cdot C_l(t,\tau_{\text{red}},M_0) \]  

(2)

where: \( \Delta f(\eta_\sigma t) \) – function for taking into account the nonlinear component of concrete creep deformations;

\[ \eta = \sigma/R_b \] – long concrete compression rate;

\( \tau_{\text{red}} \) – reduced time of action of elevated temperatures, counted from the start of heating and adopted by the method [1]:

\[ \tau_{\text{red}} = \int_{\tau_0}^{T} F(t^o) \cdot dT; \]  

(3)

\( \tau_0 \) – time value corresponding to the start of heating;

\( T \) – time value for which the creep strain of concrete is calculated.

\[ \tau_{\text{red}} = \int_{\tau_0}^{\tau} F(t^o) \cdot d\tau \]  

(4)

\( \tau_{\text{red}} \) – reduced time of action of elevated temperatures, counted from the start of heating to the beginning of the application of the load.

\( C_l \) – specific strain of linear creep of old drying concrete under isothermal heating, determined in general by the method [1]:

\[ C_l(t,\tau_{\text{red}},M_0) = \theta(t,\tau_{\text{red}},M_0) \cdot \{1 - \beta(t) \cdot \exp[-0.05 \cdot (T_{\text{red}} - \tau_{\text{red}})]\}, \]  

(5)

where \( \beta(t) \) – coefficient of accounting for the fast-flowing part of concrete creep deformations [1]:

\[ \beta(t) = 0.85 \cdot [1 - 0.0027 \cdot (t^0 - 20)] \]  

(6)

\[ \theta(t^o,\tau_{\text{red}},M_0) = \theta(t^o,\tau_{\text{red}} = 0,M_0) \cdot \{(0.07 + t^o \cdot 10^{-3}) + (0.93 - t^o \cdot 10^{-3}) \cdot \exp[-(0.08 + t^o \cdot 6 \cdot 10^{-4}) \cdot \tau_{\text{red}}]\}. \]  

(7)

In relation to high-strength concrete based on the analysis of experimental data [3, 4], the following expressions are recommended for the functions included in formulas (2) and (7):

\[ \Delta(\eta_\sigma t^0) = 0.5 \cdot \eta_\sigma \cdot (1 + \eta_\sigma) \cdot [1 + 1.5 \cdot (t^0 - 20) \cdot 10^{-3}]; \]  

(8)

\[ \theta(t^o,\tau_{\text{red}} = 0,M_0) = 0.77 \cdot \{12.7 - 0.018 \cdot t^o - 9.3 \cdot \exp[-0.01 \cdot (t^o - 20)]\} \cdot 10^{-5} \cdot \gamma_{c,M_0}; \]  

(9)

where \( \gamma_{c,M_0} \) – function to take into account the effect of structural massiveness (scale factor) on ultimate values of specific creep strain of concrete [3, 4]:

\[ \gamma_{c,M_0} = 0.6 + 0.4 \cdot (M_0/30)^{1/2} \]  

(10)

\( M_0 \) – modulus of the open surface, defined as the ratio of the area of the side surface of the structure open for drying to its volume (m\(^{-1}\)).

3. Results and Discussion

A comparison of the results of calculating the specific creep strain \( C(t,\tau) \) with the experimental data [3, 4] for high-strength modified concrete of class B80 is presented in Fig. 1.

Graphs illustrating the effect of elevated temperatures and the level of long-term compression of concrete on the change in its creep deformations are presented in Fig. 2. The calculated values of the non-linear component of the creep deformations are presented in Fig. 3. The values of the scaling factor influence function are shown in Fig. 4.

A comparison of the results of calculating the creep deformations of concrete of classes B80 ÷ B90 at heating temperatures of +90°, +150° and +200°C with the experimental data [3, 4] indicate their satisfactory convergence.

Expressions (1) ÷ (10) can be recommended for the calculated assessment of creep deformations of high-strength modified concrete for the range of temperature effects from +20° to +200°C, with long-
term compression levels $\eta_0 = 0.3 \div 0.6$. The largest deviations of the calculated values from the experimental values characteristic of more massive samples do not exceed 15% (Fig. 1 b).

**Figure 1.** The effect of elevated temperatures on the specific creep deformation of high-strength concrete [3, 4] at a long compression level $\eta_0 = 0.5$ for prism samples with dimensions: a) 150x150x600 mm, $M_0=30 \text{ m}^{-1}$; b) 250x250x650 mm, $M_0=16 \text{ m}^{-1}$
Figure 2. Influence of the heating temperature and the level of prolonged compression on the limiting values of the specific creep strain of ordinary (1 ÷ 3) and high-strength (4) concrete

1 ÷ 3 – experimental curves for medium-strength concrete of classes B25 – B35 with compression levels \( \eta_c = 0.5, 0.4 \) and 0.2, respectively, according to [1, 2];
4 – experimental points [3, 4] at a compression level of \( \eta_c = 0.5 \) and a theoretical curve according to formulas (2) ÷ (10)

Figure 3. The effect of elevated temperatures and the level of prolonged compression on the nonlinear components of creep deformation of high-strength concrete

A comparison of the calculated values of specific creep strains with the experimental data for high-strength concretes indicates that the experimental values exceed the calculated ones by 0.5–15% in the range of temperatures elevated to +200°C.

4. Conclusions
1. Modern high-strength modified concrete is less prone to long-term deformation in comparison with conventional medium-strength concrete.

2. The limiting values of the specific creep strain of high-strength modified concrete at comparable levels of long-term compression are lower than those of ordinary medium-strength concrete, on average, by 36% at a temperature of + 20°C and by 63% at a temperature of + 200°C [1, 2, 3, 4].

3. With an increase in the level of long-term compression from \( \eta_c = 0.2 \) to \( \eta_c = 0.5 \), the specific creep strain of ordinary concrete of medium strength increases at all heating temperatures up to
+200°C, on average, by 28% [1, 2], and in high-strength concrete with an increase in the level of long-term compression from \( \bar{\sigma}_0 = 0.3 \) to \( \bar{\sigma}_0 = 0.6 \), the increase in the similar value was about 40% [3, 4].

4. The specific creep strain of high-strength concrete at a long compression level of \( \bar{\sigma}_0 = 0.5 \) with increasing heating temperature from +20°C to +200°C increases 1.8 times [3, 4], and for medium-strength concrete – 3.1 times [1, 2].

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