On the Determination of the Influence of Low Negative Temperatures on Deformability and the Development of the Microcracks Forming Process in Concrete Elements under Axial Compression

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Abstract. Diagrams of axial, lateral and volumetric strains of concrete elements under axial compression in the conditions of low negative temperatures (in the frozen state) are built. It has been established that concrete specimens in the frozen state have increased strength and increased limits of axial, lateral and volumetric strains under axial compression. The diagrams of lateral strains coefficient are built. The dependencies connecting the changes in the values of coefficient of lateral strains of the concrete with variable parameters of its stress-strain state under negative temperatures action are investigated. Based on the analysis of change patterns in lateral, axial and volumetric strains, patterns of microcracks forming in concrete elements in a frozen state are established. The influence of low negative temperatures on the change of parametric points (levels) of stress-strain state of concrete, characterizing the lower and upper boundaries of microcracks forming regions is established. The results of these investigations are used for the development for the diagram method calculating of reinforced concrete structures, designed for use in conditions of low negative temperatures.

1. Types of recording of concrete strains under axial compression in the conditions of low negative temperatures diagrams

There are two types of recording of concrete strains under axial compression diagrams proposed in the work [1, 2]:

\[ \varepsilon_b = \frac{\sigma_b}{E_b \nu_b} ; \quad \varepsilon_p = -\varepsilon_b \mu_b, \quad (1) \]

\[ d\varepsilon_b = \frac{d\sigma_b}{E_b \nu_b} ; \quad d\varepsilon_p = -d\varepsilon_b \mu_b^k, \quad (2) \]

here \( \nu_b \) is the secant coefficient of axial strains of concrete (\( E_b \nu_b \) is the secant module), \( \nu_b^k \) – tangent (differential) coefficient of axial strains of concrete (\( E_b \nu_b^k \) – the tangent modulus), \( \mu_b \) – total coefficient of lateral strains, \( \mu_b^k \) – tangent (differential) coefficient of lateral strains, \( \varepsilon_b \), \( d\varepsilon_b \) – axial strains and the increments of axial strains, \( \varepsilon_p \), \( d\varepsilon_p \) – the lateral strains and the increments of lateral strains, \( \sigma_b \), \( d\sigma_b \) – compressive stresses and their increments.

Secant and tangent coefficients of axial strains according to [1, 2] are determined by dependences:
\[ \nu_b = \nu_t + \frac{\nu_o - \nu_t}{\sqrt{1 - \omega_t - \omega_o}} \]  

(3) \[ \frac{I}{v_b^k} = \frac{1}{v_b} - \frac{\eta (v_o - \nu_t)(\omega_t + 2\nu_t \eta)}{2v_o^k \sqrt{1 - \omega_t \eta - \omega_o \eta^2}}, \]  

(4)  

here the plus sign (+) is taken for the ascending branch of the diagram, minus (−) – for the descending branch, \( v_b^k \) is tangent coefficient at the beginning of the diagram (for the investigated ascending branch \( v_b^0 = 1 \)); \( \nu_t \) – tangent coefficient at the top of the diagram (at \( \varepsilon_b = \hat{\varepsilon}_b \) and \( \sigma_b = \hat{\sigma}_b \)), where \( \hat{\sigma}_b \) is axial compression stress at the top of the diagram (corresponding to prismatic compressive strength of concrete \( R_{pu} \)),  

\[ \hat{\varepsilon}_b = \frac{\hat{\sigma}_b}{E_b \nu_t}, \]  

(5)  

here \( \hat{\sigma}_b \) is axial compression stress at the top of the diagram.  

Axial compression stress level  

\[ \eta = \frac{\sigma}{\hat{\sigma}_b}, \]  

(6)  

The curvature parameter of the diagram on the ascending branch  

\[ \omega_t = 2 - 2.5 \nu_t, \omega_o = 1 - \omega_t \]  

(7)  

According to [2] at the top of the axial strains diagram  

\[ \hat{\varepsilon}_b = \frac{B}{E_b} \left( 1 + \left( 0.8 - 0.15 \frac{B^2}{10000} \right) \frac{\lambda B}{60} + 0.2 \lambda \right) \]  

(8)  

here \( \lambda \) is dimensionless coefficient, which for the investigated heavyweight concrete equals 1, \( B \) – concrete class (according to the Russian classification of concrete by compressive strength).  

Secant and tangent coefficients of lateral strains according to [1, 2] are determined by dependencies:  

\[ \mu_b = \hat{\mu}_b + \left( \mu_b^0 - \hat{\mu}_b \right) \sqrt{1 - \eta^2}, \]  

(9)  

\[ \mu_b^k = \mu_b - \frac{\eta \nu_t}{v_b} \left( \mu_b^0 - \hat{\mu}_b \right), \]  

(10)  

here \( \mu_b^0 \) is initial coefficient of lateral strains (\( \mu_b^0 = 0.15 \) according to [3]), \( \hat{\mu}_b \) – values of the lateral strains at the top of the diagram  

\[ \hat{\mu}_b = \mu_b^0 + 1 - 0.9 \cdot \sqrt{v_b}. \]  

(11)  

The researches of concrete strains in the frozen state performed by the authors at using the above-stated formulas (including respectively corrected ones) show that:  

The initial elastic modulus of concrete \( E_b \) changes to \( E_{TB} \) values, where  

\[ E_{TB} = E_b \cdot \beta_{TE}. \]  

(12)  

Stresses at the top of the diagram \( \sigma_b \) increase to values \( \sigma_{TB} = \sigma_b \cdot \beta_{TR} \),  

(13)  

Axial strains at the top of the diagram \( \hat{\varepsilon}_b \) increase to values \( \hat{\varepsilon}_{TB} = \hat{\varepsilon}_b \cdot \beta_{TE} \),  

(14)  

The axial stress level \( \eta \), which for frozen concrete is denoted by \( \eta_{TB} \), increases to the values of  

\[ \eta_{TB} = \frac{\sigma_{TB}}{\hat{\sigma}_b} = \frac{\sigma_b}{\hat{\sigma}_b \beta_{TR}}, \]  

(15)  

The secant coefficient at the top of the diagrams \( \nu_t \) changes to values \( \nu_{TB} \)  

\[ \nu_{TB} = \frac{\hat{\varepsilon}_{TB} \beta_{TE}}{\hat{\varepsilon}_b \beta_{TR} E_b \beta_{TE}} = \frac{\sigma_{TB}}{E_{TB}}, \]  

(16)  

Mathematical processing of the results of experimental studies [3] showed that the parameters \( \beta_{TE}, \beta_{TR} \) and \( \beta_{TE} \) depend on the values of negative temperatures, water-cement ratio (W/C) and the initial moisture (W, %) of concrete at the time of its freezing. At W/C=0.4 and when the moisture of concrete in the investigated range W≈4.05% – 5.11%, as well as temperature in the range t=(+20°C) ÷ (-70°C):
\[
\beta_{TE} = 1 + \left[ 0.03 + 0.12 \left( \frac{W\%-3\%}{1\%} \right) \left( \frac{20^\circ C - t^\circ C}{90^\circ C} \right) \right];
\]

(17)

\[
\beta_{TR} = 1 + \left[ 0.13 + 0.45 \left( \frac{W\%-3\%}{1\%} \right) \left( \frac{20^\circ C - t^\circ C}{90^\circ C} \right) \right];
\]

(18)

\[
\beta_{Ts} = 1 + \left[ 0.05 \left( \frac{W\%-3\%}{1\%} \right) + 0.085 \left( \frac{W\%-3\%}{1\%} \right)^2 \right] \left( \frac{20^\circ C - t^\circ C}{90^\circ C} \right)
\]

(19)

Herewith, for concrete in the frozen state remain fair dependences (1) – (10) when making the following changes: \( \dot{v}_b \) is replaced by \( \dot{v}_{rb} \), \( \eta - \eta_{r} \), \( \dot{\mu}_b - \dot{\mu}_{rb} \), where \( \dot{\mu}_{rb} = \mu_b^0 + 1 - 0.9 \sqrt{\dot{v}_{rb}} \) (20)

The volumetric strains \( \theta \) and their increments \( d\theta \) will be equal to the following:

\[
\theta = \epsilon_b (1 - 2 \mu_b)
\]

(21)

\[
d\theta = d\epsilon_b (1 - 2 \mu_b^e)
\]

(22)

2. Influence of negative temperatures on the character of diagrams of axial, lateral and volumetric strains, and tangential coefficient of lateral strains dependences on axial compression stresses also

The diagrams are built on the results of experimental and analytical researches in the field corresponding to the topic of this article. Specimens-prisms with dimensions of 15x15x60 cm of heavyweight concrete of class B35 with W/C=0.4 and initial moisture of 4.05%, 4.90%, 5.11% and 5.20% under the action of negative temperatures up to minus 70°C were tested for axial compression. Control concrete specimens of the same type were tested for comparison at positive temperature (+20°C). Mathematical processing of the results of tests was performed.

On figures 1-3 the diagrams of dependences of the axial, lateral, volumetric strains and the differential coefficient of the lateral strains on concrete axial compression stresses under negative temperatures, and for comparison at positive temperatures are shown. The values of these concrete characteristics are determined:

- theoretically, according to the formulas obtained in this article as a result of mathematical processing of the relevant experimental data [3];
- by the results of control concrete elements testing at positive and negative temperatures.

**Figure 1.** Diagram of axial and lateral strains dependences on axial compression stresses for concrete of class B35 with W/C=0.4 and moisture W=4.90% in frozen state and at positive temperature. 1 – control concrete specimens tested at +20°C; 2 – the same – at minus 70°C. Points show the results of experimental studies. The lines of the diagrams show the results of the authors’ analytical researches.
Figure 2. Diagram of volumetric strains dependences on axial compression stresses for concrete of class B35 with W/C=0.4 and moisture W=4.90% in frozen state and at positive temperature. 1 – control concrete specimens tested at +20°C; 2 – the same – at minus 70°C. Dashed lines show volumetric strains corresponding to axial compression stresses, which determine the lower $R^V_T$ and upper $R^V_T$ boundaries of concrete microcracks forming region according to authors’ analytical studies.

Figure 3. Diagram of tangential (differential) coefficient of lateral strains dependences on axial compression stresses for concrete of class B35 W/C=0.4. 1 – concrete with W=4.05% at T=+20°C; 2 – W=4.05% at T=-70°C; 1’ – W=4.90% at T=+20°C; 2’ – with W=4.90% at T=-70°C. Dashed lines – see the caption of figure 2.

Diagrams analysis shows the following:
- sufficient convergence of determining values of the axial and lateral strains results determined by experimental researches with the results of researches, determined by the formulas obtained from the mathematical processing of experimental data (figure 1);
- increasing the values of the limited axial, lateral (figure 1) and volumetric (figure 2) strains of concrete in frozen state in comparison with the corresponding strains of concrete at positive
temperatures; herewith the lower the negative temperature and the higher the initial moisture of concrete not exceeding the critical $W_c$ (between the values $W=5.11\%$ and $W=5.20\%$, see table 1) are, the greater the difference in the values of the limited strains is; the $W_c$ value here corresponds to the data of [3] to critical degree of water saturation of concrete cement stone gel pores and capillary pores ($\xi_c=90\%$).

3. Influence of negative temperatures on the change of parametric levels (points) of the stress-strain state of concrete

Parametric levels of the stress-strain state of concrete, corresponding to the lower $R^0/R_{pr}$ and upper $R^+/R_{pr}$ boundaries of microcracks forming areas, were determined by the diagrams of volumetric strains ($\theta$) changes with axial compression stresses increasing in the following way:

- the value of $R^0/R_{pr}$ was determined in accordance with the prof. O.Y. Berg’s methodology [4] at the point of concrete volumetric strains parabola maximum bending in its initial section with increasing stress of axial compression (see figure 2); the control value of $R^0/R_{pr}$ was also determined by the ultrasonic method of research at the beginning of the ultrasonic waves passage speed deviation in the direction of decreasing;

- the value of $R^+/R_{pr}$ was determined on the diagram $\theta=f(\sigma)$ by moment of the beginning of $\theta$ values decreasing with axial compression stresses increasing, i.e. by the moment of the ascending branch of the $\theta=f(\sigma)$ dependence transition to the descending branch at $d\theta=0$ (see figure 2); the value of $R^+/R_{pr}$ was also determined on the diagram of the differential (tangential) coefficient of lateral strains $\mu_{b^k}$ dependence on the compression stress when $\mu_{b^k}$ value reaches 0.5 (see figure 3);

- in the same diagram $\theta=f(\sigma)$ by authors of the article was determined for the first time the third parametric point of the region of microcracks forming concrete $R^r$; it is observed at the intersection of the descending branch of the volumetric strains curve with the ordinate axis (i.e. at $\theta=0$); this corresponds to the moment of transition of the microcracks forming process in concrete to the process of progressive micro-destructive in it with the formation of the so called [5] “magistral crack”; it is formed by connecting of the so called “bond cracks” of coarse aggregate and cement stone with “continuous cracks” in the hardened cement-sand matrix of concrete (see the work of American scientists devoted to the review of microcracks forming process in concrete [6]).

In the authors’ paper the researches of concrete elements behavior at low negative temperatures were developed for temperatures up to minus 70°C and not below. This is explained by the fact that the phase transition of water into ice finishes in gel pores and capillary pores of concrete at this temperature (minus 70°C, look through the results of experimental studies in [3]). The above is confirmed by the results of researches in the considered field of Russian [7-9] and foreign [10-12] scientists.

The results of parametric points of the concrete stress-strain state determination corresponding to the lower $R^0/R_{pr}$ and upper $R^+/R_{pr}$ boundaries of the microcracks forming area in concrete with different moisture content $W$, frozen to minus 70°C, as well as its prismatic strength $R_{pr}$, are given in table 1.

**Table 1.** Strength characteristics and parametric levels (points) of stress-strain state of concrete.

| $W_t$, % | $R_{pr}$, MPa | $R^0$, MPa | $R^+$, MPa | $R^0/R_{pr}$ | $R^+/R_{pr}$ |
|----------|----------------|--------------|-------------|----------------|----------------|
|          | $R_{pr}$, MPa |              |              |                |                |
|          | $R^0$, MPa | $R^+$, MPa | $R^0/R_{pr}$ | $R^+/R_{pr}$ | $R^0$, MPa | $R^+$, MPa | $R^0/R_{pr}$ | $R^+/R_{pr}$ |
| $W_1 = 4.05$ | 25.60 | 40.40 | 10.30 | 17.36 | 0.40 | 0.43 | 20.00 | 32.75 | 0.78 | 0.81 |
| $W_2 = 4.90$ | 24.32 | 46.00 | 9.80 | 17.85 | 0.405 | 0.39 | 19.22 | 35.70 | 0.79 | 0.72 |
| $W_3 = 5.11$ | 23.54 | 49.52 | 10.40 | 19.81 | 0.44 | 0.40 | 18.14 | 37.56 | 0.77 | 0.82 |
| $W_4 = 5.20$ | 23.34 | 33.34 | 10.00 | 16.67 | 0.43 | 0.50 | 18.24 | 22.75 | 0.78 | 0.68 |
Analysis of data in table 1 shows the following:

1. Parametric points corresponding to the lower $R_t^0$ and upper $R_t^1$ boundaries of microcracks forming areas in concrete, as well as the value of the concrete prismatic strength in the frozen state (to minus 70°C) is significantly higher than for concrete at positive temperatures;

2. The difference in the mentioned parametric points is the higher, the greater is the value of its moisture content (not exceeding the critical $W_{cr}$, definition of $W_{cr}$ see above).

4. Summary

The dependences of axial ($\varepsilon_\text{pr}$), lateral ($\varepsilon_\text{l} \theta$), volumetric ($\theta$) strains, as well as the differential (tangent) coefficient of lateral strains ($\mu^b_\text{pr}$) of concrete with different moisture content on the values of stresses (stress levels) of axial compression under conditions of low (up to minus 70°C) negative temperatures were established. These dependences are based on the analysis of the mathematical processing of experimental data results.

The diagrams corresponding to these dependences are presented in the form of relationships of concrete relative strains $\varepsilon_\text{pr}$, $\varepsilon_\text{l} \theta$, and also the differential (tangent) coefficient of lateral strains ($\mu^b_\text{pr}$) with stresses of axial compression. Parametric levels (points) of stress-strain state of concrete $R_t^0/R_\text{pr}$ and $R_t^1/R_\text{pr}$ were determined with the help of these diagrams and with the help of ultrasonic methods of the investigations.

It has been established that in frozen concrete the stress levels $\sigma/R_{\text{pr}}$ corresponding to the values $R_t^0/R_\text{pr}$ and $R_t^1/R_\text{pr}$, are increased in comparison with concrete, working in conditions of positive temperatures. The higher is the value of the initial moisture content $W_i$ of concrete (not reaching its critical value $W_{cr}$), the greater is increasing of the values of stress-strain state of concrete main levels $R_t^0/R_\text{pr}$ and $R_t^1/R_\text{pr}$.

The results of these researches are intended for the use in diagrammatics method for calculation of reinforced concrete structures, which are exploited in conditions of low negative temperatures action.

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