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# Creep of concrete at variable stresses and heating

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**Abstract.** This article gives analytical dependences for creep of concrete at heating, taking into account conditions of its drying. These dependences are based on the standard nonlinear theory of creep of concrete at a normal temperature and temperature-time analogy. For the description of creep at various stresses and temperatures the principle of superposition are used. All stages of model's creation are confirmed by the existing experimental data. Calculation examples are given.

**Keywords**: temperature; creep; concrete; mechanical properties; thermal analysis; reduced time; superposition

## 1. Introduction

Researches of longtime deformations of concrete (including creep) by the variable modes of loading and heating have, as a rule, experimental character – Nasser and Newill (1967), Hannant (1968), Fahmi *et al.* (1972), Bazant *et al.* (2004), Bazant and Cusatis (2005), Gernay and Franssen (2012), Havlasek and Jirasek (2012), Jirasek and Havlasek (2014), Yao and Wei (2014). Theoretical researches are directed, generally, on the description of simple creep (stress is constant) at stationary heating – Alexandrovskii (1973), Thelandersson (1987), Barani *et al.* (2010), Dias-da-Costa and Julio (2010), Ouedraogo *et al.* (2011), Jirasek and Havlasek (2014), Yao and Wei (2014), or creep of concrete at the loading by steps and normal temperature (Scordelis 1984, Briffaut *et al.* 2012, Trapko *et al.* 2012, Schlicke and Viet Tue 2013, Jiang *et al.* 2014). The general theoretical researches for the description of longtime deformations of concrete at the variable stresses and non-stationary temperature obviously not sufficiently. The article attempts to fill this shortcoming.

The most essential factors, which influence on the creep of heated concrete, are its initial humidity and speed of removal of moisture. Influence of these factors at the analytical description of deformations of creep is considered directly by means of their values in the set timepoints, as it is accepted in the works Hannant (1968), Fahmi *et al.* (1972), Alexandrovskii (1973), Bazant and Cusatis (2005). However, experimental control of humidity of concrete during exploitation of structures is not simple procedure. Therefore, in practice it is better to use an indirect parameter, so-called, the modulus of an open surface $m_o$ ($m^{-1}$) (Krichevskii 1984), representing the relation of

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the area of an open surface to volume. All type of concrete could be classified by this parameter on sealed ($m_o$=0) and drying ($m_o$>0). The works, devoted to studying of thermocreep of the sealed concrete are undertaken by Hannant 1968, Fahmi *et al.* 1972, Barani 2010, Briffaut *at al.*2012, drying concrete - Nasser and Newill 1967, Alexandrovskii 1973, Krichevskii 1984, Bazant 1985, Bazant and Wittman 1982, Gernay *at al.* 2013, Jirasek and Havlasek 2014. In these researches the attempts of universal description of creep of the sealed and drying concrete upon heating were made. Futher to that, various regimes of applied loading and temperatures were studies. In the basis of these researches are the standard nonlinear theory of creep of concrete at normal temperature (Alexandrovskii 1973, Pichler and Lackner 2008, Dias-da-Costa and Julio 2010, Maia and Figueiras 2012, Rossi *et al.* 2013, Jiang *et al.* 2014), the time-shift principle (temperature-time analogy) (Krichevskii 1984, Thelandersson 1987, Bazant *et al.* 2004, Barani 2010) and the principle of superposition.

## 2. Basic compliance function of concrete at a normal temperature

Deformations of concrete in the timepoint $t$ are represented by the sum of shorttime deformations $\varepsilon_e(t)$ and creep's deformations $\varepsilon_{cr}(t)$. The analytical expression for the longterm deformations in a timepoint $t$ by the constant compression $\sigma(\tau)=const$ (simple creep), loaded at time $\tau$, is

$$\varepsilon(t)=\varepsilon_e(t)+\varepsilon_{cr}(t)=J(t,\tau)\cdot\sigma(\tau)=\left[\frac{1}{E(\tau)}+C(t,\tau)\right]\cdot\sigma(\tau) \tag{1}$$

Here $J(t,\tau)$ - basic compliance function, is the deformations at time $t$ by constant stress $\sigma(\tau)=const=1$, loaded at time $\tau$ ; $E(\tau)$ - modulus of instantaneous deformations of concrete at age $\tau$ (were determined by data of works Prokopovich and Zedgenidze (1980), Ouedraogo *et al.* (2011), Youssef and Moftah (2007); $C(t,\tau)$ - basic creep compliance function at $\sigma(\tau)=const=1$. This function we represent in a form (Prokopovich and Zedgenidze 1980)

$$C(t,\tau)= f_n(\sigma)\cdot\theta(\tau)\cdot f(t-\tau) \tag{2}$$

where $f_n(\sigma)=f_n(t)$ - nonlinearity function, $f(t-\tau)$ - duration function of the loading

$$f(t-\tau)=1-ke^{-\gamma(t-\tau)}-(1-k)e^{-b(t-\tau)} \tag{3}$$

$\theta(\tau)$-the limit creep compliance function

$$\theta(\tau)=C(\infty,28)\Omega(\tau) \tag{4}$$

In these formulas $C(\infty,28)$ - limit creep compliance function of concrete (standard), loaded at the age of 28 days in 1/MPa, is determined by experimental data; $\Omega(\tau)$ - age function of concrete. Eq. (3) allows decomposition of variables and (2) can be rewritten so (Scordelis 1984)

$$C(t,\tau)=\sum_{i=1}^{3}H_i(\tau)\cdot G_i(t)=\sum_{i=1}^{3}C_i(t,\tau) \tag{5}$$

where

$$H_1(\tau)=\theta(\tau);\;\; H_2(\tau)=-k\cdot\theta(\tau)\cdot e^{\gamma\tau};\;\; H_3(\tau)=-(1-k)\cdot\theta(\tau)\cdot e^{b\tau};$$

$$G_1(t)=f_n(t);\;\;\; G_2(t)=f_n(t)\cdot e^{-\gamma t};\;\;\; G_3(t)=f_n(t)\cdot e^{-bt}.$$

Taking into account Eq. (5), basic compliance function $J(t,\tau)$ will become equal

$$J(t,\tau)=\frac{1}{E(\tau)}+\sum_{i=1}^{3}C_i(t,\tau)=\frac{1}{E(\tau)}+\sum_{i=1}^{3}H_i(\tau)\cdot G_i(t) \tag{6}$$

## 3. Creep of concrete at elevated temperatures

For the description of longterm deformations of concrete at heating up to temperature $T > 20$, °C without thermal expansion also Eq. (1) is used. However, it is known, that heating intensifies process of creep, and that the same deformations at the same stresses are reached *et al.* evated temperatures for shorter time, than at a normal temperature. Besides, strains depends not only on temperature, but also on humidity and conditions of concrete drying (Bazant and Wittmann 1982). For sealed concrete, according to experimental data (Hannant 1968, Mc Donald 1971, Briffaut 2012, Havlasek and Jirasek 2012) they slightly change, but for the drying concrete at heating up to 200 $^{o}$C they increases by 3,5-4 times (Nasser and Newill, 1967, Krichevskii 1984, Milovanov 1975, Bazant *et al.* 2004). Increases in creep strains can be considered by means of growing limit of creep strains, and also of the time-shift principle or time-temperature analogy, based on a hypothesis of parallel shift of charts of creep at elevated temperatures relative to normal temperature in logarithmic coordinates. Time $t$ is counted in a conditional scale, so-called the "reduced time" $t^*$. At the isothermal heating

$$t^*=\beta(T)\cdot t;\quad \tau^*=\beta(T)\cdot\tau \tag{7}$$

where $\beta(T)$ - time-shift function.

Approximation of the experimental results from the works, listed above, gives the following expression for time-shift function

$$\beta(T)=1+\omega\left[1-\left(0.02\frac{g(T)}{\omega}\right)^{0.376 m_o/\hat{m}_o}\right]$$

$$g(T)=1+0.308(\hat{t}-1)+0.004(\hat{t}-1)^2;\; \hat{t}=T/20;\; \omega=1.02g(T)-1. \tag{8}$$

Here $\hat{m}_o = 10$ m$^{-1}$ is the module of an open surface of standard prism 10×10×40 cm.

The materials, satisfying to a hypothesis of parallelism of curves of creep in the logarithmic coordinates, are called the "thermo rheological simple". Many authors consider, that concrete is the such material (Hannant 1968, Mc Donald 1971, Fahmi *et al*. 1972, Thelandersson 1987). But in works (Bazant and Wittman 1982, Barani *et al*. 2010) this hypothesis isn't confirmed.

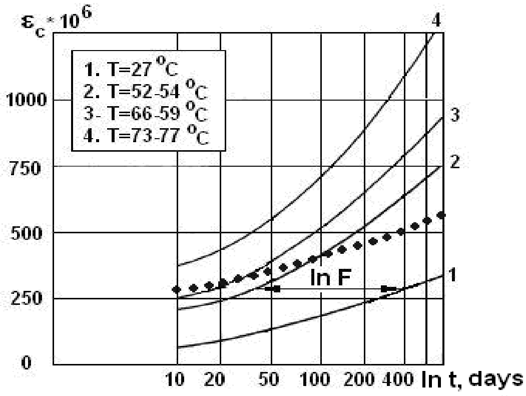


Fig. 1 Strains of creep of concrete at compression and heating

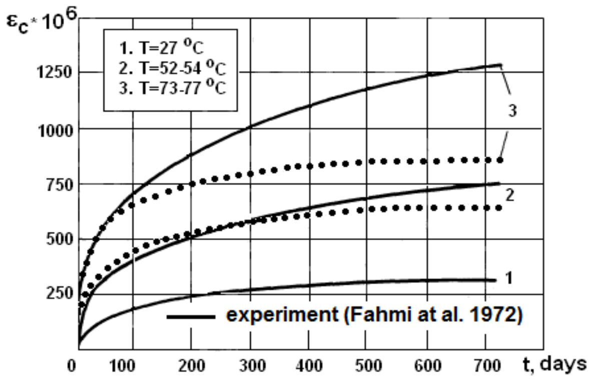


Fig. 2 Check of a hypothesis of parallelism

By example taken from experimental data (Hannant 1968), we will show that concrete isn't thermo - rheological simple material. In Fig. 1 creep's strains are shown in logarithmic coordinate for the hot sealed concrete. Mechanical characteristics of concrete: compressive strength $f_c$=60 MPa, the modulus $E_b$=40000 MPa. Stress is equal $\sigma$=14.06 MPa. The same curves are presented in Fig. 2 in real time scale. Evidently, that curves of creep at various temperatures aren't parallel. Similar results can be received according to work (Fahmi *et al.* 1972). It is obvious, that the theoretical curves for the elevated temperatures, constructed on Eq. (7), have to be turned to parallelism to a curve at a normal temperature. The size of logarithmic shift depends not only on temperature, but also from duration of heating. Therefore time-shift function we will present so

$$\beta(T,t) = \beta_1(T)\beta_2(t) \tag{9}$$

Function $\beta_1(T)$ is determined by a Eq. (8). Function $F_2(t)$ considers relative turn of curves. Approximation of the experimental data from works Hannant (1968), Bazant and Wittman (1982), Barani *et al*. (2012), allows to recommend the following expression for this function

$$\beta_2(t) = a\,t^{-b} \tag{10}$$

where $a$≈6.13a; $b$≈0.3.

Influence of temperature on creep is estimated not only by means of shift time. During heating creep's limit $C(\infty,28)$ and nonlinearity's functions $f_n(\sigma)$ are changes.

All parameters, necessary for definition of a basic creep compliance function Eq. (2), received on the basis of various sources, at normal and elevated temperatures are specified in Table 1,

Table 1 Parameters of creep of concrete at normal and elevated temperatures

| Param. | Normal temperature $T$=20$^o$C | Elevated temperature $T$>20$^o$C ($\hat{t}=T/20$) |
|---|---|---|
| $\gamma$ | $\gamma = \gamma_o = 0.01\text{-}0.006e^{-0.36(m_o/m_o-1)}$ $m_o / m_o \geq 1$ (Prokopovich and Zedgenidze 1980) | $\gamma = \gamma_r = \gamma_o.$ |
| $B$ | $b = b_o = 0.6$ (Prokopovich and Zedgenidze 1980) | $b = b_T = b_o.$ |
| $k$ | $k = k_o = 0.8$ (Prokopovich and Zedgenidze 1980) | $k = k_o[1+0.054(\hat{t}-1)]$ (Krichevskii 1984) |
| $\tau,\ t$ | $\tau = \tau_o,\ t = t_o$ | $\tau = \tau^* = \beta(T,t)\tau_o,\ t = t^* = \beta(T,t)t_o$ |
| $f_n(\sigma)$ | $f_n(\sigma) = f_n^o(\sigma) = 1 - v_c(\sigma / f_c)^{n_c}$, $v_c = v_c^o = 0.74\left[1+2.027e^{-0.107(f_c-12.5)}\right]$, $n_c = n_c^o = 4$; (Prokopovich and Zedgenidze 1980) | $f_n(\sigma) = f_n^T(\sigma) = 1 - v_c^T(\sigma / f_{cT})^{n_c^T}$ $v_c^T = v_c^o + 0.26(\hat{t}-1),\ n_c^T = n_c^o + 0.2(\hat{t}-1)$ (Milovanov 1975) |
| $\Omega(\tau)$ | $\Omega(\tau) = d_o + (1-d_o)e^{-\xi\tau}$, $d_o = 0.5, \xi = 2\gamma$ (Prokopovich and Zedgenidze 1980) | $\Omega(\tau^*) = d_T + (1-d_T)e^{-\xi\tau^*}$, (Milovanov 1975) $d_T = d_o\left\{1-\omega\left[1-\left(0.02\frac{q}{\omega}\right)^{0.376m_o/\dot{m}_o}\right]\right\}$, $q = [0.157(\hat{t}-1) - 0.858\ln\hat{t}]$, $\omega = 1-0.98q$ |
| $C(\infty,28)$ | $C(\infty,28) = C_o(\infty,28)$ | $C(\infty,28) = C_T(\infty,28) = C_o(\infty,28)\left[1+\alpha\left(1-e^{-0.1(\hat{t}-1)}\right)\right]$ $\alpha = 3.802\left(1+1.496e^{-0.2(\hat{t}-1)}\right)$ (Alexandrovskii 1973) |

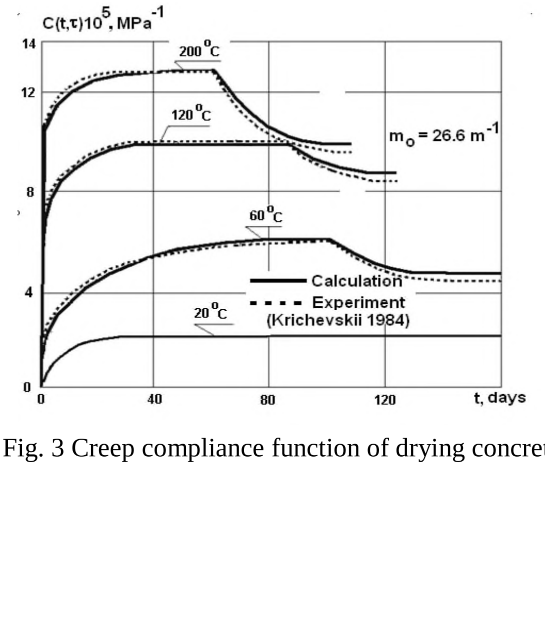


Fig. 3 Creep compliance function of drying concrete

where $f_c$ - strength of concrete on compression in MPa at normal temperature, $f_{cT}$- strength in MPa at temperature T, °C.

On a Fig. 3 specific basic creep compliance function of the drying concrete, calculated by a Eq. (2), taking into account tabl. 1 and experimental data from work Krichevskii (1984) are presented.

## 4. Creep of concrete at variable stresses and temperatures

We consider, that the creep is function of stresses and temperatures, which aren't constants during supervision time. Full strains at the time *t* can be found with the help of integral

$$\varepsilon(t) = \int_0^t d\varepsilon \tag{11}$$

Using the principle of superposition and Eq. (6), will write down

$$\varepsilon(t) = \int_0^t d[J(t,\tau)\cdot\sigma(\tau)] == \int_0^t d\left\{\left[\frac{1}{E(\tau)} + \sum_{i=1}^{3} C_i(t,\tau)\right]\sigma(\tau)\right\} \tag{12}$$

We will designate

$$d\varepsilon_e = d\left[\frac{\sigma(\tau)}{E(\tau)}\right] \quad \text{and} \quad dB_i = H_i(\tau)\cdot d\sigma(\tau) + \sigma(\tau)\cdot dH_i(\tau) \tag{13}$$

we will get

$$\varepsilon(t) = \int_0^t d\varepsilon_e + \sum_{i=1}^{3} G_i(t)\cdot\int_0^t dB_i = \varepsilon_e(t) + \sum_{i=1}^{3}\varepsilon_c^i(t) \tag{14}$$

Will define strains in a timepoint $t + dt$ as

$$\varepsilon(t+\Delta t) = \int_o^{t+dt} d\varepsilon \tag{15}$$

or

$$\varepsilon(t+dt) = \int_0^{t+dt} d[J(t+dt,\tau)\cdot\sigma(\tau)] = \int_0^{t+dt} d\left\{\left[\frac{1}{E(\tau)} + \sum_{i=1}^{3} C_i(t+dt,\tau)\right]\sigma(\tau)\right\}$$

or

$$\varepsilon(t+dt) = \int_0^t d\left\{\left[\frac{1}{E(\tau)} + \sum_{i=1}^{3} C_i(t+dt,\tau)\right]\sigma(\tau)\right\} + \int_t^{t+dt} d\left\{\left[\frac{1}{E(\tau)} + \sum_{i=1}^{3} C_i(t+dt,\tau)\right]\sigma(\tau)\right\} \tag{16}$$

Using designations Eq. (13), we will receive

$$\varepsilon(t+dt) = \varepsilon_e + \int_t^{t+dt} d\varepsilon_e + \sum_{i=1}^{3} G_i(t+dt)\cdot\int_0^t dB_i + \sum_{i=1}^{3} G_i(t+dt)\cdot\int_t^{t+dt} dB_i$$

Finally

$$\varepsilon(t+dt)=\varepsilon_e(t)+\int_t^{t+dt} d\left[\frac{\sigma(\tau)}{E(\tau)}\right]+\sum_{i=1}^{3}G_i(t+dt)\cdot\left\{\frac{\varepsilon_c^i(t)}{G_i(t)}+\int_t^{t+dt}\left[H_i(\tau)\cdot d\sigma(\tau)+\sigma(\tau)\cdot dH_i(\tau)\right]\right\} \quad (17)$$

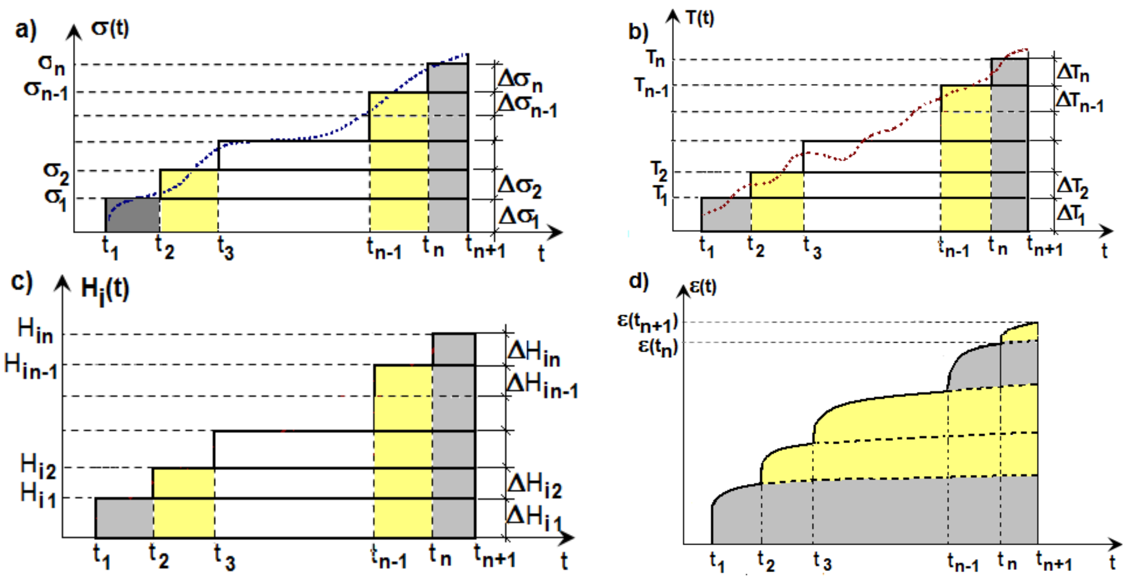


Fig. 4 Strains of concrete at variable stresses and temperatures

Thus, there was a received equation for definition of full strains at time $t+dt$ as the sum of strains at time $t$ and increments of strains at the period $dt$. For definition of these increments it isn't required to know the history of the previous deformation, because the limits of integrals in Eq. (17) are equal $t$ and $t+dt$.

To integral Eq. (17) we will apply procedure of numerical integration by the rule of rectangles. We will divide all time interval into parts. We will designate borders of these parts so $t_1, t_2,\ldots,t_{n-1}$, $t_n$, $t_{n+1}$. We consider, that the beginning of parts coincides with the time of the steps of loading and (or) heating. Increments of stresses on intervals we will define so $\Delta\sigma_1\,\Delta\sigma_2\ldots\,\Delta\sigma_{n-1}\Delta\sigma_n$ (Fig. 4(a)) and for temperatures so $\Delta T_1\,\Delta T_2\ldots\,\Delta T_{n-1}\,\Delta T_n$ (Fig. 4(b)). Temperature in Eq. (17) isn't present at an obvious form, however directly determines material's parameters $H_i$. Therefore for each time interval, the increment of temperature is an equivalent to an increment of parameters $H_i$ ($i$=1,2,3), i.e., $\Delta_1 H_i\,\Delta_2 H_i\ldots\,\Delta_{n-1} H_i\,\Delta_n H_i$ (Fig. 4(c)).

Having replaced the differentials by the corresponding increments in Eq. (17), we will receive a recurrent formula for calculation of longterm deformations which, taking into account thermal expansion, will equal

$$\varepsilon(t_{n+1})=\varepsilon_e(t_n)+\frac{\Delta\sigma_n}{E_n}+\sum_{i=1}^{3}G_i(t_{n+1})\left\{\frac{\varepsilon_c^i(t_n)}{G_i(t_n)}+\left[H_i(t_n)\cdot\Delta\sigma_n+\sigma_n\cdot\Delta H_i(t_n)\right]\right\}+\alpha_n\cdot\Delta T_n \quad (18)$$

We will note, that the modulus of short-term deformations $E_n$ and coefficient $\alpha_n$ both depends from age and temperature. For its definition were used data of works Alexandrovskii (1973), Milovanov (1975), Krichevskii (1984), Prokopovich and Zedgenidze (1980), Youssef and Moftah (2007), Ouedraogo *et al.* (2011).

## 5. Verification of model

In Fig. 5 is given the example of calculation of creep's strains of concrete at a normal temperature by stresses of $\Delta\sigma$=±20.8 MPa and comparison with results of experiments in work by Alexandrovskii (1973). Initial data: $f_c$=27.8 MPa, $m_o$=10 m$^{-1}$, $C(\infty, 28)$=0.00003 MPa$^{-1}$, $T$=20$^o$C.

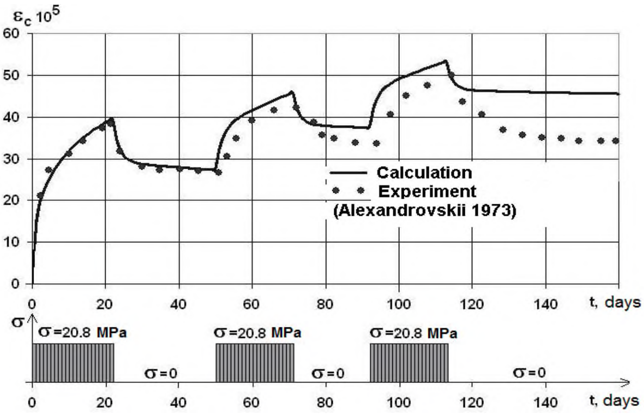


Fig. 5 Creep of sealed concrete at variable stresses

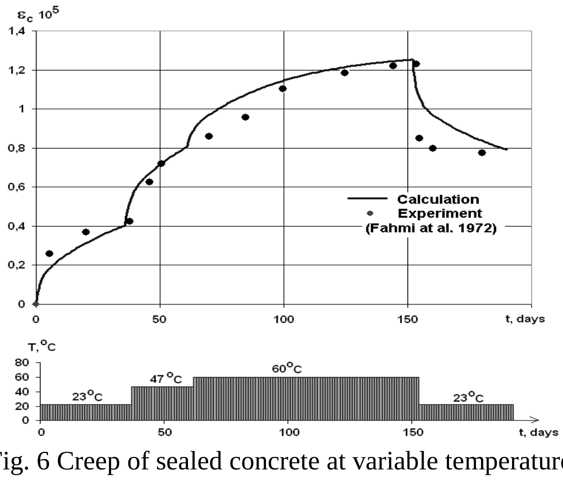


Fig. 6 Creep of sealed concrete at variable temperatures

In Fig. 6 is given the example of calculation of creep deformations of sealed concrete at variable temperatures by constant stresses $\sigma$=1 MPa, and comparison with experimental data Fahmi *et al*. (1972). In Fig. 7 we present an example of calculation of creep strains of the drying

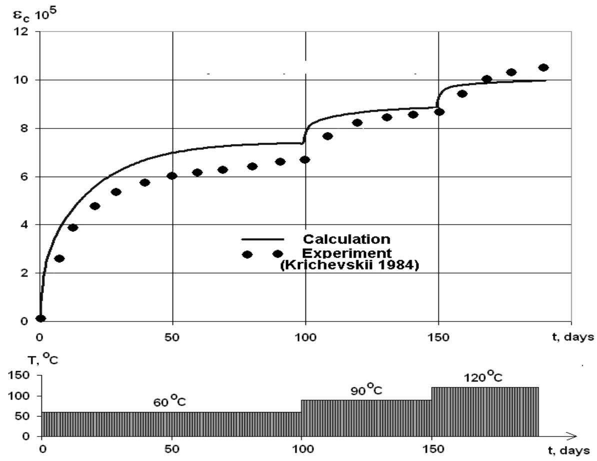


Fig. 7 Creep of drying concrete at variable temperatures

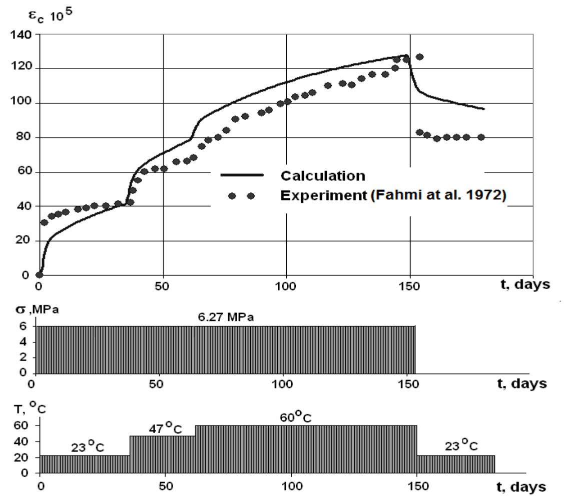


Fig. 8 Creep of sealed concrete at variable temperatures and stresses

concrete at variable temperatures by constant stresses $\sigma$=1 MPa and comparison with experiments (Krichevskii 1984). Results of calculation are obtained for the initial data: $f_c$=27.8 MPa, $m_o$=30 m$^{-1}$, $C(\infty,28)$=0.000045 MPa$^{-1}$. At the last in Fig. 8 presents the example creep's deformations of sealed concrete at variable stresses and temperatures on a Eq. (18) and comparison with experimental data (Fahmi *et al.* 1972). Regimes of the applying of loading and temperature are presented in the same drawing. Results of calculation are received at the following initial data: $f_c$=42.2 MPa, $m_o$=2 m$^{-1}$, $C(\infty,28)$=0.000065 MPa$^{-1}$. It is evident, that the complete calculation and experimental data coincide.

## 6. Conclusions

On the basis of available experimental data we have received analytical dependences for parameters of the nonlinear theory of creep at elevated temperatures. It results in assessment of conditions of drying of heated concrete which considerably influence numerical values of creep's deformations. It is established that function shift of time, considering influence of heating on creep of concrete, depends not only on temperature of heating, but also on its duration. There are rather simple step by step algorithms of calculation of creep strains of concrete at various regimes of loading and heating, which allow to do without storage of all intermediate results, keeping them only on the previous step. The given calculations and comparison to the experimental data confirm reliability of offered analytical dependences.

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