Modeling of viscoelastic strain and creep for hardening structures based on cement under temperature gradients

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Abstract

During the hardening period, materials based on cement experience deformation due to heat generation and moisture movement or internal consumption of water by cement. All these processes influence the change of material volume. As a result, these factors can lead to water tightness problems, durability problems and damage due to frost, which means that numerical simulation of its properties is important problem. So, in order to predict and prevent these problems, a numerical model should be developed in a proper way. For example, accurate consideration of heat generation and heat loss should be incorporated to calculate the temperature distribution gradients. The first goal of the research is to present numerical model of temperature calculation and then using this data to estimate thermal dilation and autogenous shrinkage during the contraction phase. As is well known, creep also influences on stress state for hardening materials and is a relaxation factor during the cooling period. Finally, the aim is to model a creep effect.

1 Introdiction

As is well known early age concrete behaviour may lead to crack initiation within structures. Scientists have explained it by happening of the high thermal stresses within massive concrete elements. Such measure as using the cooling of the structure has resulted, in some cases, in the surface cracks due to the internal restraints. All these processes happen due to the volumetric deformation within casting concrete structure. and can result in deterioration and damage in structure or degradation of the serviceability. Meanwhile, the presence of cracks and their propagation should be controlled in the details. Generally, to predict and prevent deterioration mechanisms it is significant to model early age deformation in casting concrete and understand the mechanism of deformation occurrence.

The total deformation in young concrete consists of stress-dependent and stress independent deformations. Two driving forces such as thermal dilation and shrinkage are included in the stress-independent deformation and creep effect makes a contribution in stress independent deformation. These deformations depend on the temperature history. There are two methods of determination of the temperature distribution in a structure. One of them is to solve the heat transfer equation, another is applying the heat balance. The describing of these methods for young concrete could be find in references literature [1] – [3]. In this paper the heat balance is used for finding of the temperature field.

The empirical equations for estimation of the concrete shrinkage have been developed in many theses. E.Holt [4] has described the understanding of the mechanisms due to shrinkage under no moisture movement from or to surroundings (autogenous shrinkage). H.Hedlund [5] has shown the evaluation of shrinkage in three different ways. For example, as a function of relative humidity, based on degree of reaction and combining these methods. In the article, modelling of shrinkage was made by maturity function without moisture transfer through a structure.

The investigation of creep could be carried out by different methods, such as Rate of flow method (RF), Effective modulus method (EM) , Method of superposition, Rate of Creep method (RC), Improved Dischinger method (ID), Trost-Bazant method (TB), Rheological models (RM) and Double power law (DPL) model. In the paper, the calculations of creep effect are made by DPL-model.

The main task here is to develop the model for accurate calculations of stress-dependent and stress-independent deformations.

2 Model for temperature profile

As was mentioned in the introduction the distribution of the temperature is determined by the heat balance between the heat development due to the hydration reactions and heat loss with surroundings.

The factors affect the temperature distribution in the young concrete are:

1. thermal properties (heat of hydration, conductivity and heat capacity);
2. geometry and size of structure;
3. boundary conditions (air temperature, formwork, insulation, and etc);
4. initial conditions (fresh casting temperature).

Hydration process could be presented through the hydration degree which is determined as the ratio of the hydration heat to the ultimate hydration heat.

$$\alpha(t) = \frac{Q(t)}{Q_u(t)}$$

where $\alpha(t)$ is the degree of hydration at time t, Q(t) is the heat of hydration at time t, $Q_u(t)$ is the ultimate heat of hydration.

Heat of hydration is presented as exponential function in the form [6]

$$Q(t) = Q_\infty \cdot e^{\left[-\left(\frac{\tau}{M(t)}\right)^{\alpha}\right]}$$

where Q_∞ is the total value of the heat generation, τ and α are the model parameters, M(t) is the maturity function describing the effect of the temperature on the rate of the heat reactions.

Maturity function based on Arrhenius equation is written as [7]

$$M(t) = \int_0^t e^{-\frac{E(T)}{R}\cdot\left(\frac{1}{T(\tau)}-\frac{1}{T_{ref}}\right)} \cdot d\tau$$

where E(T) is the activation energy and equal to

$A + B \cdot (T - 20)$ for $T > 20$°C or A for $T < 20$°C,

T_{ref} is the reference temperature, $T(\tau)$ is the function of the temperature, R is the universal gas constant.

In this paper, it is proposed that the heat loss from structure to surroundings takes place due to convection. Newton's law defines the heat transmission to surroundings as

$$q = h_c \cdot (T_S - T_A)$$

where q is the convective heat flux per unit area A, h_c is the convective coefficient, T_S and T_A are the surface temperature against environmental temperature. Regarding the different temporary covers the equivalent convective coefficient h_c' is found as [8]

$$h_c' = \frac{1}{h \cdot A} + \sum_{i=1}^{n} \frac{L_i}{k_i \cdot A}$$

where L_i is the thickness of i-curing cover and k_i is the conduction coefficient of i-material. Regarding the initial conditions, next conditions are used

$$T(x, y, t_0) = T_0$$

Finding the temperature profile with regarding the affects described early are made by the next equation

$$T = T_{init} + \int dT_{dev} - \int dT_{loss}$$

where T_{init} is the casting temperature, $\int dT_{dev}$ expresses the increase of the temperature due to the chemical reactions, $\int dT_{loss}$ expresses the decrease of the temperature due to the heat loss.

3 Model for stress-independent deformation

In the hardening concrete, there are two driving forces involves the time-dependent deformation that influence the crack initiation. If we consider isothermal conditions (T=const), autogenous shrinkage effects alone, under normal conditions, where temperature changes occasionally, thermal dilation and autogenous shrinkage operate to produce stresses [3]

$$\varepsilon_{tot} = \varepsilon_T + \varepsilon_{as},$$

where ε_{tot}— total deformation, ε_T — thermal deformation and ε_{as}— autogenous shrinkage.

Larson's method can be used to describe the thermal deformation in the details. This method applies only for contraction phase and does not consider the warm period. Tensile stress occurs from second zero stress time t_2 and after second zero stress temperature T_2 .

Time t_2 is more than time t_1 when structure starts cooling (see Fig. 1) and could be expressed as [9]

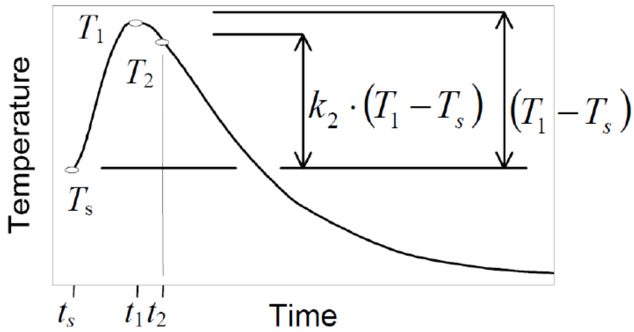

Figure 1: Temperature distribution in hardening period. Tensile stress occurs after time t_2 .

$$T_2 - T_s = k_2 \cdot (T_1 - T_s)$$

where T_s is the temperature corresponding to time t_s, T_1 is the maximum temperature on the surface of the structure and $k_2 = 1.41 - 1.36 \cdot (w/b)$.
k_2 - factor as we could notice depends on the cement type and has been developed in Sweden. After calculation T_2, at a given point of time t_3 ($t_3 > t_2$), thermal dilation is found as [3]

$$\varepsilon_T = \alpha_T \cdot (T_3 - T_2)$$

where α_T is the thermal expansion coefficient.

The thermal expansion coefficient α_T depends on the type of aggregate and as a literature indicates is in range of $(5.6 - 13) \cdot 10^{-6}$ 1/°C, but if α_T is unknown, in this case, standard value $10 \cdot 10^{-6}$ 1/°C is used for calculations.

In the hydration process, in spite of the thermal deformation the changes in volume may exist due to shrinkage which occurs because of the moisture transfer through a structure or internal consumption of water by cement. Process of a concrete volume change when moisture flow is negligible is called autogenous shrinkage. It is only a result of internal chemical and structural reaction of the concrete composition.

The evaluation of the autogenous shrinkage is determined, in this paper, as a time function based on the hydration rate. The autogenous shrinkage starts to develop is in the interval from 9 to 24 hours. As a rule, starting time for autogenous shrinkage development is usually chosen to be 24 maturity hours after casting. The autogenous shrinkage $\varepsilon_{sh}(t)$ as a function of time may be written as [5]

$$\varepsilon_{sh}(t) = \varepsilon_{su} \cdot \beta_{s0}(t) \cdot \beta_{ST}(T)$$

where ε_{su} is the final value (ultimate) of autogenous shrinkage,
$\beta_{s0}(t)$ is the relative time of autogenous shrinkage development,
t is the age of concrete.

Distribution of the autogenous shrinkage as a function of time is expressed [5]

$$\beta_{s0}(t) = e^{-\left(\frac{t_{s0}}{t - t_{start}}\right)^{\eta_{sh}}}$$

where t_{start} is the starting time of autogenous shrinkage development (arbitrary time, but not before t_0),
t_{s0}, η_{sh} are the empirical constants. For different concrete composition, these values could be taken from paper [5].

The temperature effects on the autogenous shrinkage may be defined by [5]

$$\beta_{ST}(T) = a_0 + a_1 \cdot (1 - \exp(-(T/T1)^{b1})) + a_2 \cdot (1 - exp(-(T/T2)^{b2}))$$

The total deformation from time t_2 to t_3 is figure out in the next form [3]

$$\varepsilon(t_2, t_3) = \varepsilon_T + \varepsilon(t_2, t_3)$$

4 Model for stress-dependent deformation

When concrete is subjected to constant loads, further deformations will develop after the instantaneous deformation. This phenomenon, of the viscoelastic behaviour, is well known as a creep. Fig.2 shows that the creep is partly reversible deformation. Reversible deformation is relatively small, but it is significant to consider the viscoelastic behaviour of the immature concrete in order for accurate calculations.

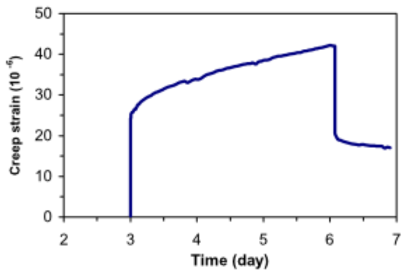

Figure 2: Compressive creep and creep recovery of a HPC specimen.

In this investigation, Double power law (DPL) is used and the basic creep of concrete is determined by the creep function as [3]

$$J(t, t') = \frac{1+\phi(t,t')}{E(t'_e)} \text{ and } \phi(t, t') = \phi_0 \cdot t'^{-d} \cdot (t - t')^p$$

where t_e is the maturity function (or equivalent time), t'_e is the maturity time at loading. t is the actual time, t' is the actual time when the stress increment is applied, and ϕ_0, d and p are the DPL model parameters.

Deformation reflects the creep could be written in the next way

$$\varepsilon = \int_0^t J(t, t') \cdot d\sigma(t')$$

5 Simulation results

In this research the infinite wall is considered. It means that only the wall thickness is considered in calculations. Calculations are made for 28 days. Input data are used for concrete B65. The wall thickness is equal to 4m, the insulation thickness is equal to 0.012m (see fig.3). Thermal conductivity of wood and for hardening concrete are equal to 0.67 kJ/(m·h·°C) against 5.9 kJ/(m·h·°C). The heat capacity is equal to 0.84 kJ/(kg·°C).

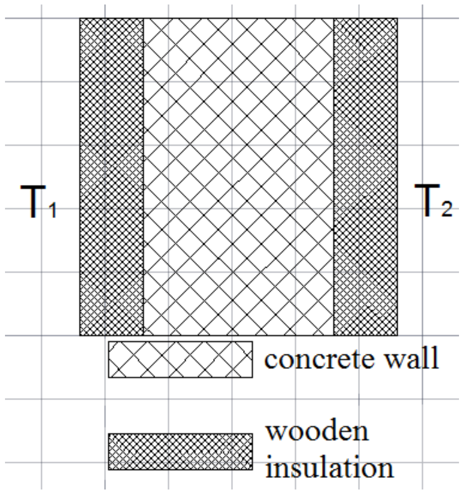

Figure 3: The scheme of the concrete wall.

The analyzed concrete wall consists of cement density - 450 kg/m^3, water density - 160 kg/m^3 and the total density of the concrete mix is equal to 2610 kg/m^3. It is supposed that in 28 days after casting the wooden insulation is removed . In accordance with the hydration model next parameters are used: $\alpha = 2.45, \tau = 10.99$ h and $Q_\infty = 314$ kJ/kg cem. For calculations of the activation energy A=33.5 kJ/mol and B=1.47 kJ/mol·°C. The total strain involves in the stress independent deformation is calculated by using the next coefficients:t_{s0}=120 h, t_{start}=24h, η_{sh}=0.3, a_0=0.4, a_1=0.6, a_2=0.1, b1=2.9, b2=7, T1=9°C, T2=55°C. Calculations of the creep effect based on the next parameters:ϕ_0=0.33, d=0.27, p=0.56.

The modelling of the temperature and deformations are carried out under different environmental temperatures T_1 and T_2 (see.Fig. 3) where T_1=12°C and T_2=16°C. The initial temperature of the concrete wall is equal to 15°C.

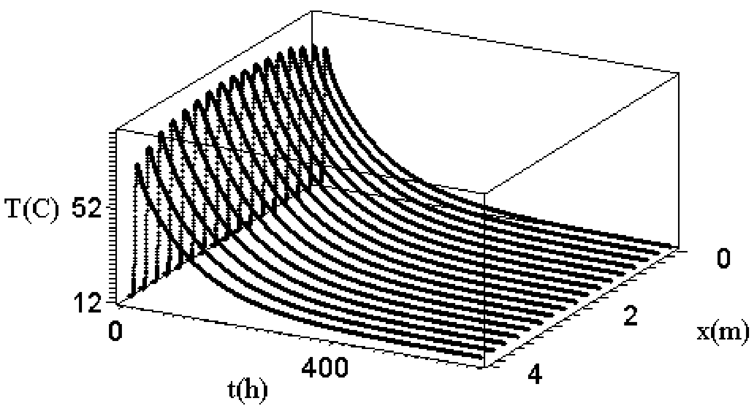

Figure 4: Surface of the temperature distribution through a wall .

Fig. 4 represents the changes in temperature in a wall over the time. Various temperatures in massive concrete occur because hydration, i.e. exotic reactions generated huge amount of heat. The core of the massive concrete elements become hot due to concrete has low thermal conductivity and then it cools down due to dominate of heat loss under heat of hydration. In 28 days the the temperature profile is a linear function.

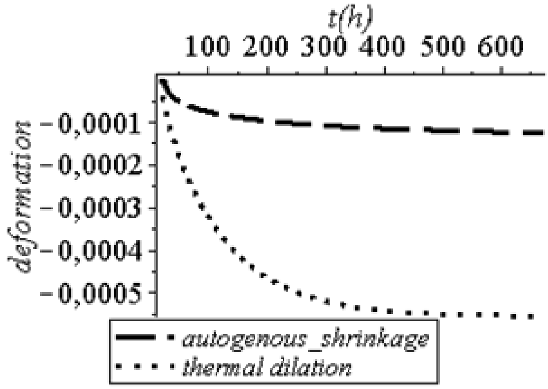

Figure 5: Parts of time-independent deformation.

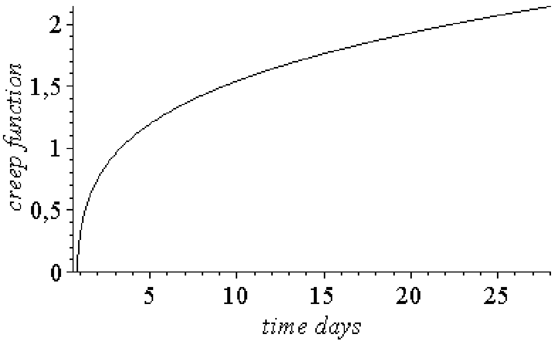

Figure 6: Creep function.

Graph 5 shows the autogenous shrinkage against thermal deformation. The total strain, in accordance with the equation - $\varepsilon(t_2, t_3) = (T_3 - T_2) \cdot \alpha_T + \varepsilon(t_2, t_3)$ is a little bit more than the thermal strain.

According to DPL-model creep function is calculated and shown on the Fig. 6

Proposed model for the calculations of the thermal strain and viscous deformation as a creep in the concrete wall allows to make thermal-stress analysis for concrete wall more accurately.

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