A contribution to the analytical description of concrete deformation under transient temperatures

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1 INTRODUCTION

Concrete has been used already for quite a long time as a structural material for massive structures installed in plants for energy generation or storage of energy carriers.

In applications such as safety containments, reactor pressure vessels, etc. the concrete is generally exposed to continuous high operating temperatures of about 120 °C. Apart from that, temperature impacts up to 300 °C resulting form accidents have to be taken into consideration. Due to the temperature impact, changes are induced in the mechanical and physical properties of the concrete /1/. The elevated temperatures have an influence not only on the strength behaviour and the structural changes of the concrete but also on its deformation behaviour, which plays an important part in the interaction between concrete and metal internals (liner, stand pipes, penetrations, etc.).

The general deformation behaviour of concrete as a function of load, temperature and time is shown in Fig. 1.

In this article the deformation behaviour of concrete is analyzed under transient temperatures. (Range II in Fig. 1). This range is characterized by the phenomenon that the concrete deformation at increasing temperatures is several times that of the concrete deformation at stationary temperatures.

To analyse the deformation behaviour of concrete under a time-dependent temperature change, numerous experimental analyses have been performed at the Technical University of Braunschweig. Tests have been performed on cylindrical basalt concrete specimens of 150 mm and 30 mm diameter and 300 and 240 mm lengths. Concrete quality B55 according to DIN, concrete age 215 d, soaked in water.

The test specimens were analyzed under various load levels and immediately after the application of load they were heated to maximum temperature at a heating rate of 5 k/h.

The load level of α = load/short-term strength was varied from about 0.0 to 0.02, 0.3, 0.5, 0.6, 0.7. During

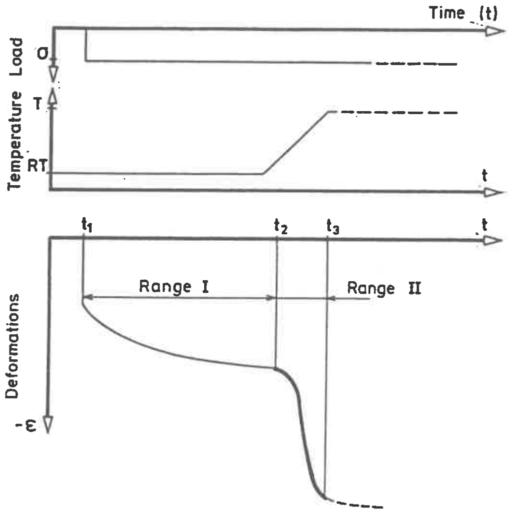

Fig. 1: General Curve of Time-Dependent Concrete Deformation as a Result of Load and Temperature

this test the concrete deformations were measured. The measuring results were then analysed numerically with the objective to describe the concrete deformations by a mathematical formula.

The overall deformation of concrete at an age τ as a function of time (t), temperature (T) and load (σ) can be described by the following equation.

(1) $$\varepsilon(T,t,\tau) = \varepsilon_{\sigma}(\tau_I) + \varepsilon_T(T,t,\tau_I) + \varepsilon_{\sigma}(T,t,\tau_I)$$

The individual functions describe:

$\varepsilon_{\sigma}(\tau_I)$ - Deformation of concrete at an age τ_I immediately after application of load (σ)

$\varepsilon_T(T,t,\tau_I)$- Deformation of concrete resulting from thermal expansion

$\varepsilon_{\sigma}(T,t,\tau_I)$- non-elastic fraction of deformation

The non-elastic fraction of deformation can be described as follows:

(2) $$\varepsilon_{\sigma}(T,t,\tau) = \phi_1(\sigma,T) \cdot \phi_2(t-\tau_I) \cdot \phi_3(\tau_I)$$

ϕ_2 = function of heating rate; ϕ_3 = function of concrete age

(3) $$\phi_1(\sigma,T) = \left[f_1(T) + \frac{A_1 - f(\sigma)}{A_2} \cdot f_2(T)\right] \cdot f(\sigma)$$

where f_1 (T) and f_2 (T) = modified creep functions, $f(\sigma)$ - stress function; A_1, A_2 constant parameters

This form of equation (3) represents the optimum description of the non-elastic fraction of concrete deformation at a relatively wide range of loads $0 \leq \alpha \leq 72$ %.

In addition, a computer code has been established for the description of concrete deformations at transient temperatures.

2 ELASTIC AND THERMAL DEFORMATIONS

The elastic deformation of the concrete $\varepsilon_{\sigma}(\tau_I)$ at the age τ_I was determined on the basic of the analytical dependence σ-ε following the Eurocode recommendation /5/ and can be described by the following equation:

$$(4) \qquad -\sigma = \frac{A \cdot \eta - \eta^2}{1 - B \cdot \eta} \cdot C$$

where: $\eta = -\varepsilon/D$; A,B,C,D = constant parameters experimentally determined.

The measuring results and the by (4) described σ-ε curve are shown in Fig. 2.

The function of the thermal expansion $\varepsilon_T(T,t,\tau)$ was determined in analogy to /2/ by using own test results. The analytical processing of the measuring results was performed in accordance with /3/ and /4/. This resulted in the following equation:

$$(5) \qquad \varepsilon_T(T,t,\tau) = a \cdot x^3 + b \cdot x^2 + c \cdot x + d$$

where a,b,c,d are constant parameters, x = temperature parameter.

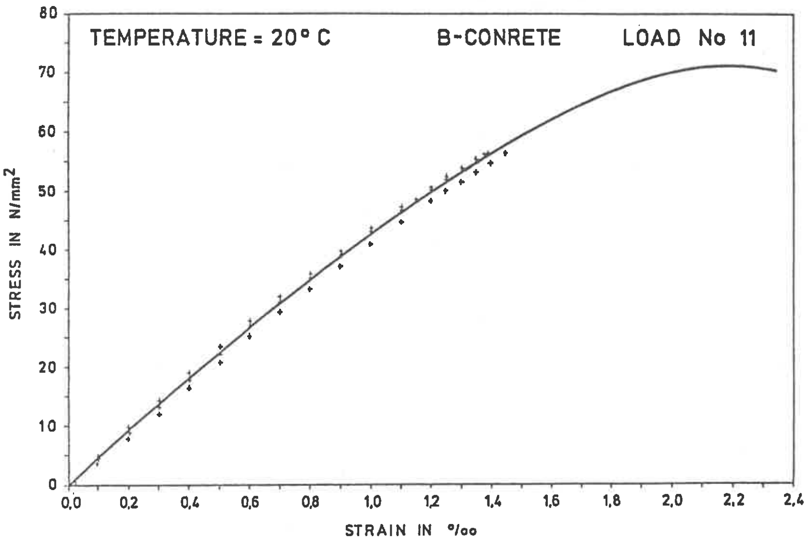

Fig. 2: Stress-Strain Relationsship of B-Concrete Calculated and Measured Values

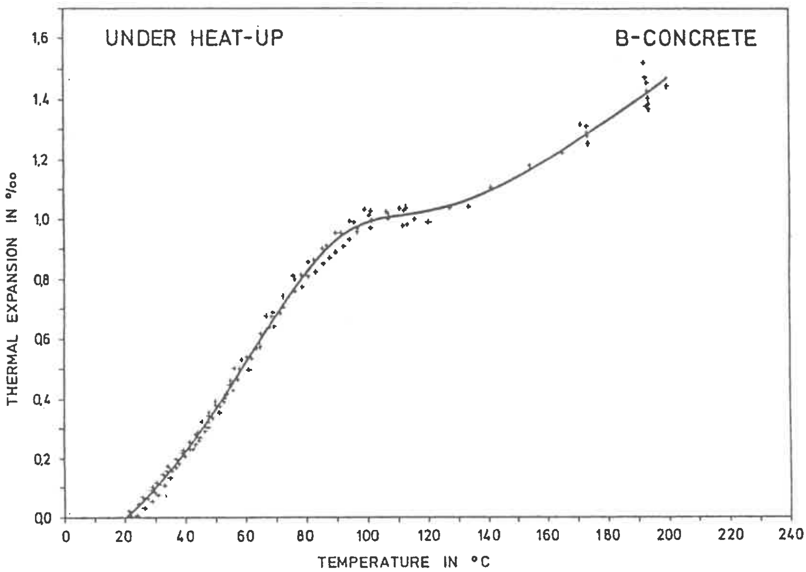

Fig. 3: Thermal Expansion of B-Concrete; Calculated and Measured Values

Both data groups are defined for specific temperature intervals.

The calculated results and measurements are shown in Fig. 3.

3 CREEP DEFORMATION

It is suggested to describe the expansion increment at the time t after the beginning of heat-up of a concrete under load at the age τ_I by the equation (2) given above.

A mathematical description of the functions $\phi_2(t-\tau_I)$ and $\phi_3(\tau_I)$ will only be possible after additional experiments will have been conducted about the influence of concrete age and heat-up rate on the expansions to be analysed. In the present case the influence parameters were constant, therefore it was assumed:

$$\phi_2(t-\tau_I)\Big|_{\dot{T}=5\,K/h} = 1{,}0 \quad \text{and} \quad \phi_3(\tau_I)\Big|_{\tau_I=215\,d} = 1{,}0$$

This means that the contribution presented in this place is only of limited validity.

The function $\phi_1(\sigma,\tau)$ - creep function - (cf. equ. 3) has been developed on the basis of a comprehensive numerical analysis. It is the optimum function to give a mathematical representation of the concrete deformations discussed above. The stress function f (σ) contributing to the equation is described as follows:

(6) $f(\sigma) = \beta \cdot \sigma^{p}$

Taking into account the stress function defined in (6), the modified creep functions $f_1(T)$ and $f_2(T)$ can be represented as follows:

(7) $$f_1(T) = a_1 \cdot x^3 + b_1 \cdot x^2 + c_1 \cdot x + d_1$$

(8) $$f_2(T) = a_2 \cdot x^3 + b_2 \cdot x^2 + c_2 \cdot x + d_2$$

The constant parameters and influence parameters given below are used in equations (3) and (6-8):

$\beta = 2.55$, $p = 1.25$, $A_1 = 1.25$, $A_2 = 0.55$

$a_i, b_i, c_i, d_{i/(i=1,2)}$ = constant parameters and x = a temperature parameter, determined for specific temperature intervals.

4 SUMMARY AND OUTLOOK

The total deformation of concrete as a function of time, temperature and load under transient temperatures can be described with a relatively high accuracy by equation (1).

The load level to be taken into consideration can be covered in a range between 0 and about 70 %.

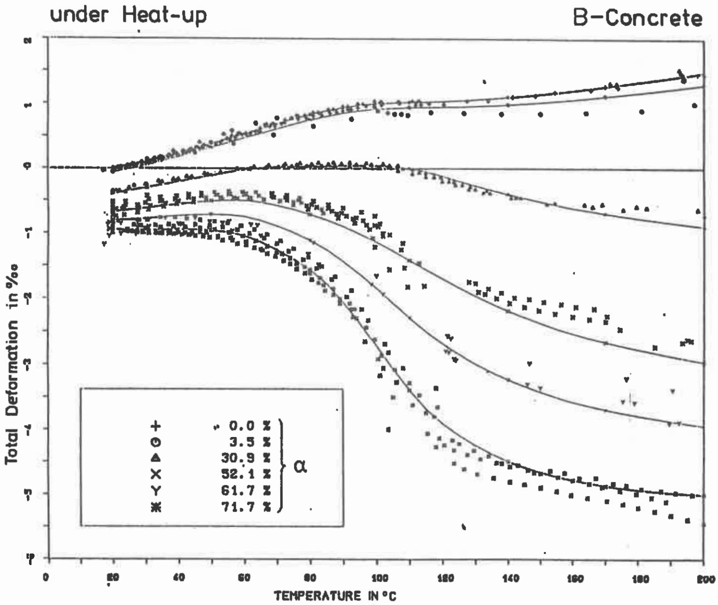

Fig. 4: Total Deformation of Concrete under Heat-up and Various Load Levels; Calculated and Measured Values

Fig. 4 shows an example of the agreement between measurements and calculated results.

It has thus been possible to establish an analytical description of an important material characteristics. Supplemented by some completions, this could be of great assistance in the computational analysis of specific massive concrete structures.

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