Restraint Behaviour of Concrete Under Extreme Thermal and Hygral Conditions

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1. Introduction

Stresses due to temperature may be a considerable part of the whole loading of the structure especially in reactor vessels, chimneys and other structures. During using of this structures the heating cycle consisting of heating and cooling may be repeated for several times. On the other hand the initial load, the preloading time, the heating rate and the moisture of concrete can differ in respect of the design or utilisation of the structure. The effect of this environmental factors on the restraint behavior of concrete is presented in this paper.

2. Test program

2.1. Test procedure

According to the conditions which can exist in a prestressed containment during its usage and to the possibilities which are offered by the test apparatus the following parameters for the testing process were chosen:

- max. temperature	130°C
- rate of heating	5, 8.5 and 12 K/h
- initial load	0.11, 0.23, 0.35 and 0.48*R^c(cyl.stren.)
- preloading time	1h and 24h
- moisture	sealed 100%r.h.
	unsealed 65 %r.h.

The running off of the test is shown in Fig.1. All tests were repeated for statstical reasons. A specimen made from a concrete mixture of quarzite gravel and cement PZ 7/35 with an unaxial compressive cylinder strength of 23 N/mm^2 was used. The composition of the concrete is given in (Schwesinger 1987b). Every test consists of two heating cycles, in doing so the second cycle starts seven days after the beginning of the first one.

2.2. Test apparatus

According to the test program stress and strain controlled tests were realized. For uniaxial loading a servohydraulic device was used. The strains were measured with inductive strain gauges. in doing so it was possible to keep it constant with a inexactitude of ±0.5µm. The heating device consists of three heating units, three resistance thermometers, three temperature controllers and a controlling device for the heating rate. All measured values were recorded. The sealing of the specimen is realized by a metal case in which elastic openings are present for the measuring mark holders of the strain measurement (Schwesinger 1986). In the remaining gap between the concrete surface and the metal case 150 ml water were added.

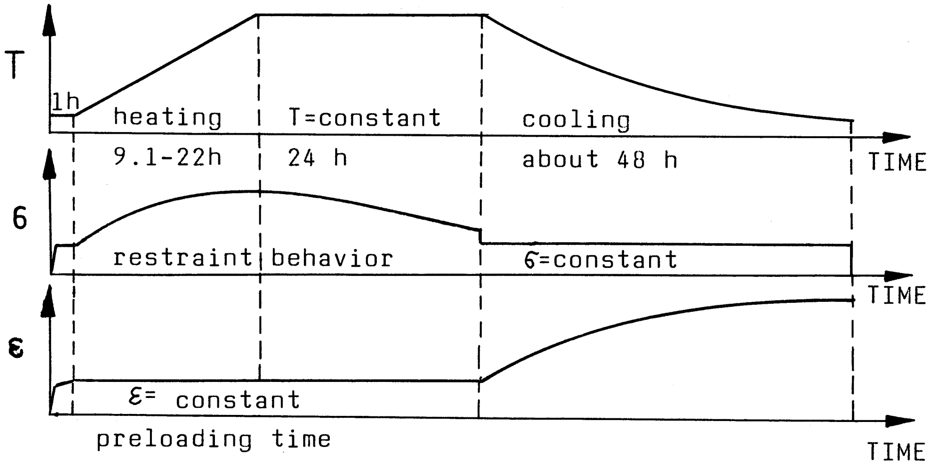

Fig.1 Test process and parameters

Ⓐ heating units
Ⓑ strain gauge
Ⓒ Invar steel bar
Ⓓ metal case of stainless steel
Ⓔ specimen
Ⓕ insulating plate
Ⓖ hydraulic flat jack
Ⓗ lower part of test frame
Ⓘ servohydraulic valve
Ⓚ pressure gauge
Ⓛ upper part of test frame
Ⓜ insulating plate,steel pl.
Ⓝ temperature gauge

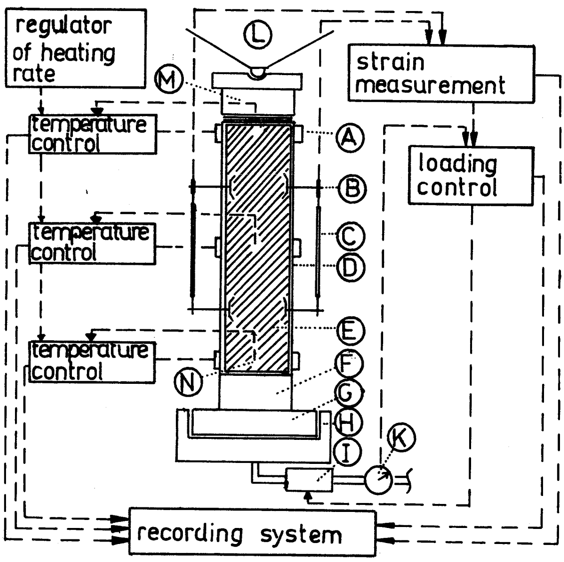

Fig.2 Test apparatus

3.Results
The development of thermal stresses depends on the ratio of speed of thermal strain to speed of creep of concrete. For all parameters investigated like initial load, preloading time, heating rate and moisture a clear influence on the restraint behavior of concrete could be found. A lower initial load causes a steeper ascent of the curve of thermal stresses (Fig.3). Therefore the maximum of stress occurs later at a temperature of 70°C. Comparing the curves it can be seen, that all initial loads cause nearly the same level of stress in the last part of the heating cycle. In the second heating

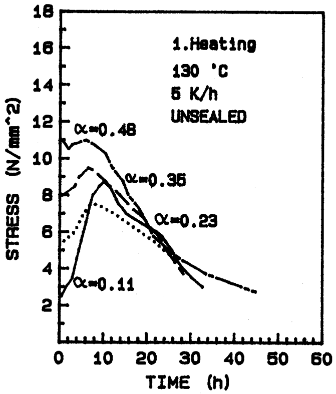

FIG.3 Influence of initial load

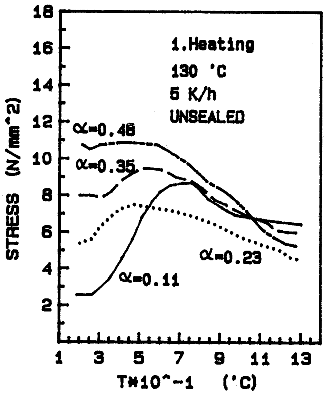

FIG.4 Influence of initial load

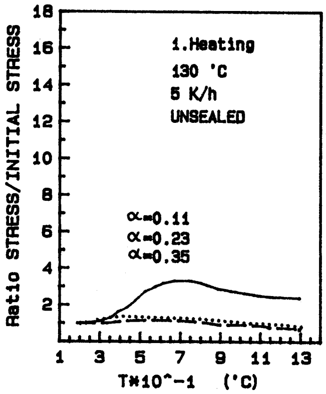

FIG.5 Influence of initial load

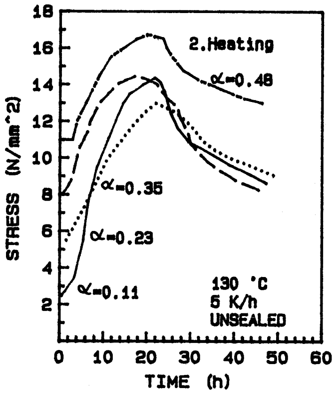

FIG.6 Influence of initial load

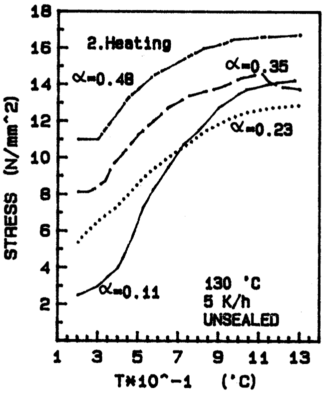

FIG.7 Influence of initial load

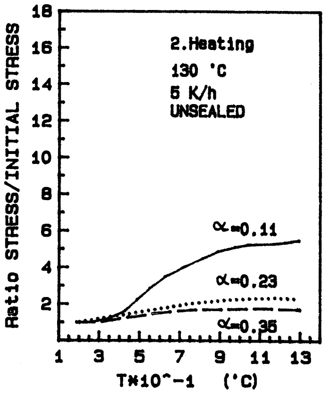

FIG.8 Influence of initial load

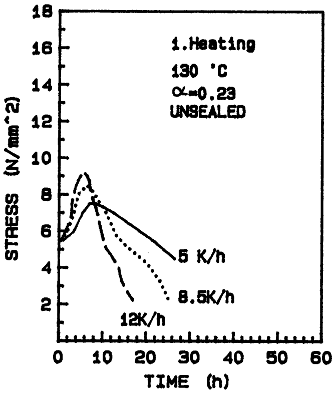

FIG.9 Influence of heating rate

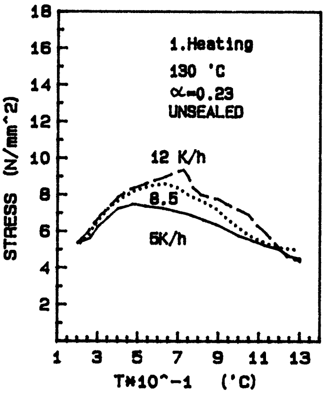

FIG.10 Influence of heating rate

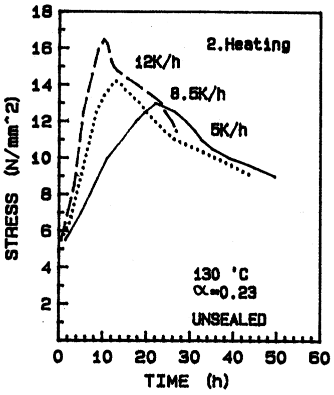

FIG.11 Influence of heating rate

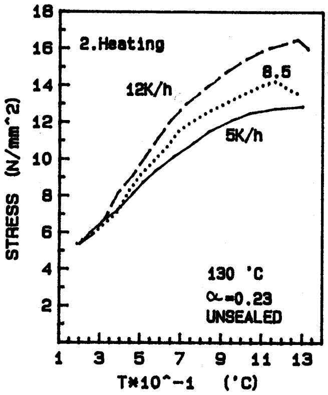

FIG.12 Influence of heating rate

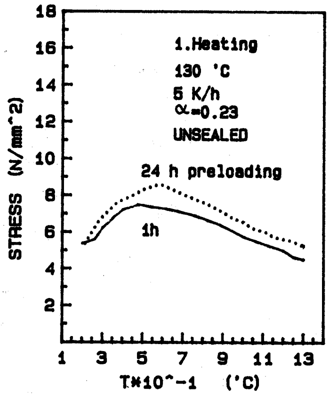

FIG.13 Influence of preloading

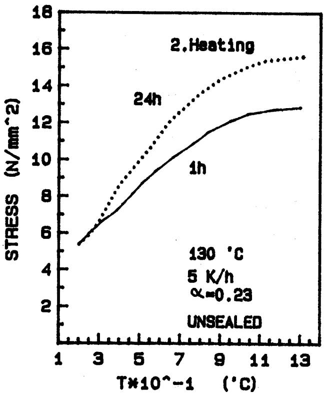

FIG.14 Influence of preloading

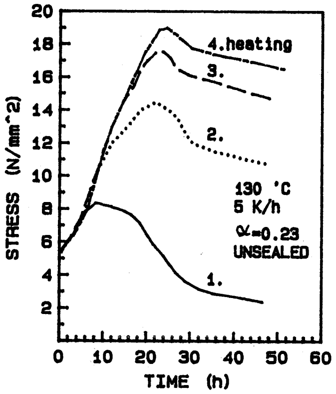

FIG.15 One test with 4 heatings
Time between the beginning of
the heatings = 7d

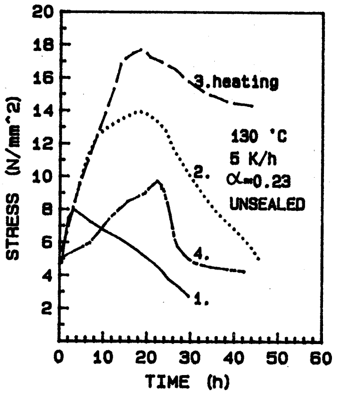

FIG.16 One test with 4 heatings
Between 3.and 4.heating cured
in water for 50d

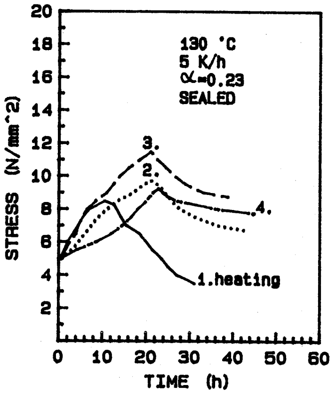

FIG.17 One sealed test; Time
between the 1.2.and 3.heating =4d
between the 3.and 4.heating =14d

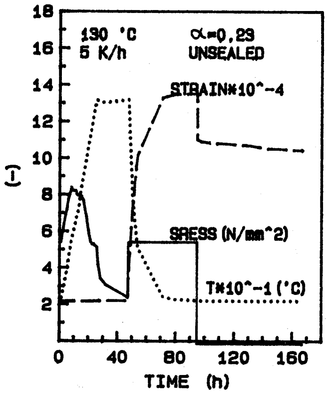

FIG.18 Stress strain and
temperature during the first
heating

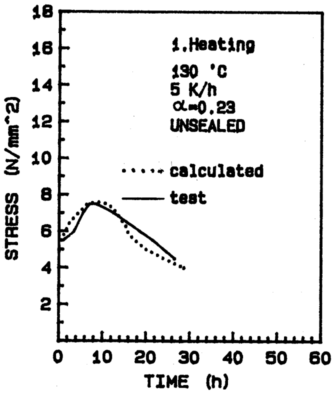

FIG.19 Predicted and measured
stresses during first heating

cycles a variation of higher initial loads causes only a parallel shifting of the curves. The influence of rate of heating on the development of thermal stresses is more evident (Fig.9,10,11 and 12). Starting from the supposition that the thermal strain occurs contemporary with the elevation of the temperature it must be concluded that the transient thermal creep deformation show a certain inertia. This could be confirmed in the second heating cycle. At a preloading of 24h the ascent of the curves rises similar like at the elevation of the heating rate up to 12K/h (Fig.10,13,12 and 14). This shows the importance of basic creep in the first hours after applying the load. In the following Figures tests with more than two heating cycles are presented. The heating cycles are generally repeated after every week, except in Fig.16 and 17 in which the specimen was cured in water between the 3. and 4. heating cycle. The thermal stresses of the 4. cycle of Fig.16 are much lower than in the previous one. That means that the concrete is able to regenerate the transient thermal creep potential during a rest period in water at ambient temperature. This was also to be found by (Khoury 1985). The difference in the behavior of the curves of the repeated heating cycles in the sealed test is lower than in the unsealed one. Moisture can obtain the creep potential above several heating cycles. A regeneration of the transient thermal creep potential between the 3. and 4. heating cycle could also be obtained in this test. In all tests could be found, that the maximum of thermal stresses occured at about 60°C in the first heating cycle and at the end of the heating in the second one. The ascent of the curves in the first hours after beginning of the first heating cycle is the same than in the second cycle.

4.Prediction of thermal stresses

As mentioned above the development of thermal stresses depends on the ratio of speed of thermal strain to speed of creep of concrete.

$$\dot{\sigma} = E(T) * (\dot{\varepsilon}_{th} - \dot{\varepsilon}_{cr}) \qquad (1)$$

Equ.1 is created by (Schneider 1979). For the prediction of the creep deformation an equation of (Müller 1986) and (Budelmann 1987) was applied. To this equation a 4. part - the transitional thermal creep - has been added.

$$\varepsilon_c = \varepsilon_r + \varepsilon_{bc} + \varepsilon_{dc} + \varepsilon_{ttc} \qquad (2)$$

$-_{r}$ retarded elastic strain
$-_{bc}$ basic creep
$-_{dc}$ drying creep
$-_{ttc}$ transitional thermal creep

In the investigations transitional thermal creep was found to be the most important part of creep deformations during the first and second heating cycle and therefore has the largest influence on the restraint behavior of concrete. The function of the free thermal strain was found in own tests:

$$\alpha_T = 1.54942*10^{-5} - 3.9*10^{-8}*T \qquad T \text{ in } °C \qquad (3)$$

The modulus of elasticity was calculated with an equation of (Budelmann 1987).

$$E(T) = (1-(T-20/350)*E(20) \qquad T \text{ in } °C \qquad (4)$$

The creep deformations at variation of stress $\Delta\sigma$ were predicted by superposition of the creep values calculated with $\Delta\sigma$. Doing so it was found, that even a variation of stress at 0.5 N/mm^2 per hour causes only a very small change of creep values compared with transitional thermal creep.

Therefore the Equ.1 could be simplified to:

$$\sigma(t) = E(t) * (\varepsilon_{th}(t) - \varepsilon_{cr}(t)) \qquad (5)$$

The creep deformation was calculated with an average changing of stresses. The function of transitional thermal creep

$$\varepsilon_{ttc} = a * (t - t_0) \qquad t \text{ in h; a in } \frac{1}{h} \qquad (6)$$

was found to be the simplest to achieve a good agreement between the stresses calculated and investigated. To give an example thermal stresses were predicted and presented in Fig.19. For the shown parameters the factor a is set to 0.0012.

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