Restraint Forces of HTR-Concrete during Heat-up to 300°C

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1 INTRODUCTION

In course of research and development for the prestressed concrete vessel of the HTR 500 high-temperature reactor there have been performed comprehensive analyses concerning technology and thermomechanical behaviour of the concrete. The tests were initiated by Hochtemperatur-Reaktorbau GmbH and executed by the Institut für Baustoffe, Massivbau und Brandschutz. Some of the results of previous studies concerning creep and strength at service and accident temperatures up to 600°C have already been published (see Becker, 1984; Weber & Diederichs 1985; Diederichs, 1986).

However, up to now there are no established concepts at hand to estimate the restraint stresses with sufficient accuracy. Thus, restraint tests were necessary to gather the needed reliable data for elaboration and confinement of a constitutive model.

The restraint tests, which are reported on in the following, are strongly related to the real conditions in the PCRV as far as initial mechanical stresses and heating rate are concerned. The hygral regimes in the PCRV, which effect the development of the restraint forces to a great extend, are due to lack of data and calculation methods not yet sufficiently and accurately predictable. Thus, only the two limit states of moisture regimes could be included in the test programme: free evaporation of water (so-called unsealed heating) and complete prevention of the water evaporation (so-called sealed heating). Besides, the preconditioning of the specimens was varied. After demoulding one part of the specimens was cured under water until testing to obtain complete hydration of the cement paste; the other part was wrapped into aluminium and plastic foils and hydrated under these sealed conditions to simulate the real conditions in the PCRV structure.

2 EXPERIMENTAL

The restraint tests were performed with cylindrical specimens (diameter 8 cm, length 30 cm). The mix proportions of the investigated HTR-concrete (basalt concrete) as well as the data of the fresh and hardened concrete are already reported in detail by Weber et al. (1985) and Diederichs (1986). The specimens were casted in steel moulds and demoulded after one day. Part of the cylinders were stored under water for at least 90 days until testing (water cured specimens) and part of the specimens were wrapped in a combination of aluminium foils and plastic foils to provide water vapour tight sealing (sealed cured specimens).

The specimens were tested under unsealed as well as under sealed conditions. Sealing was provided by a specific bellow as shown in fig. 1. With the unsealed specimens the physically and chemically bound water could freely evaporate. - The testing procedure was as follows (comp. fig. 2): The specimens were installed in the testing machine and loaded three times with 15 N/mm^2 to determine the modulus of elasticity at 20°C. Thereafter they were loaded again with the desired initial stress σ_i (8 N/mm^2 resp. 15 N/mm^2). The deformation due to the initial load (ϵ_i) was measured and kept constant during heat-up to 250°C (sealed specimens) respectively 300°C (unsealed specimens) with constant heating rate of 5 K/h. There were recorded the restraint forces, but also the water vapour pressure in the sealing device and the surface temperature of the specimens.

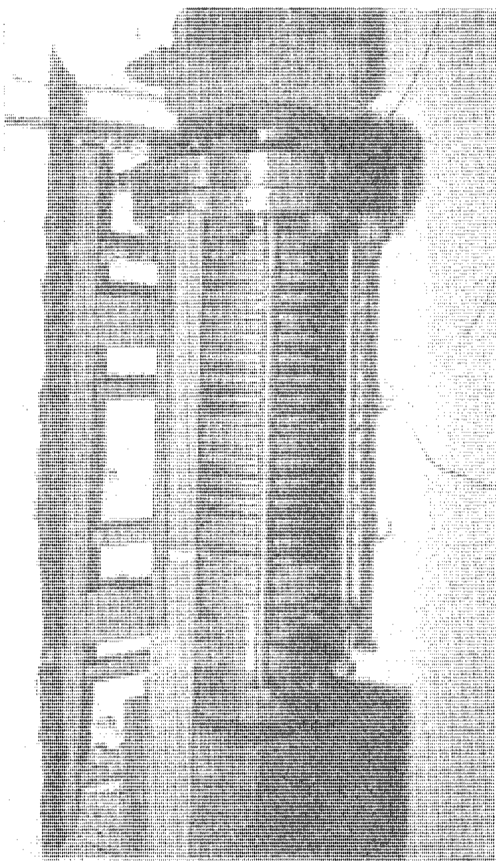

Fig. 1: Sealing device equipped with thermocouples, dilatometer rods and pressure gauge

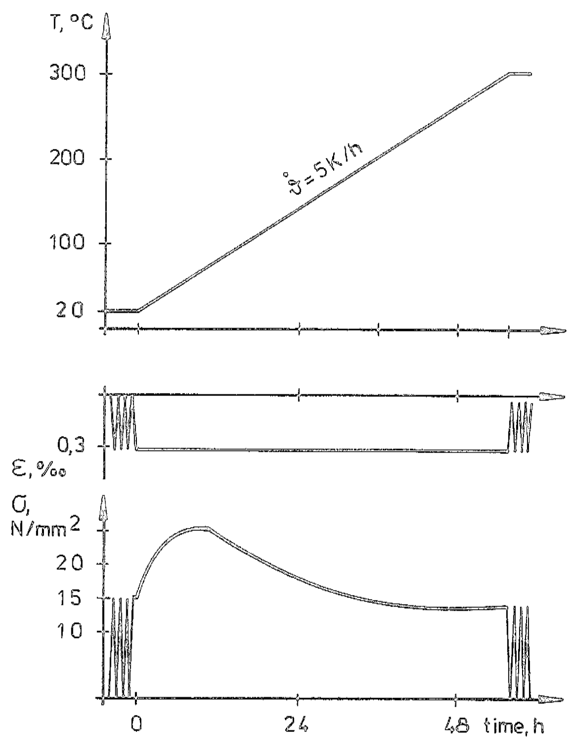

Fig. 2: Schematic representation of the test procedure

Prior to cooling the modulus of elasticity measured again, after cooling the weight loss and the resudial strength were determined.

In order to obtain reliable data for each type of test three specimens were investigated. Table 1 gives the survey over the complete test programme.

Table 1: Test programme

max.temperature, °C	curing conditions	heat-up conditions	initial load level, N/mm^2	number of specimens
250°C	soaked under water	sealed	8 15	3 3
	sealed cured	sealed	8 15	3 3
300°C	soaked under water	unsealed	8 15	3 3
	sealed cured	unsealed	8 15	3 3

3 RESULTS AND DISCUSSION

The development of the restraint forces of unsealed heated specimens are shown in figs. 3, 4 and 5. At the beginning of heating, in the temperature region 20°... 65°C, the restraint forces increase nearly independently of the specific test conditions (e.g. initial stress σ_i) almost linearly with temperature. Above 65°C the further increase of the restraint forces declines. Subsequently the restraint forces reach their maximum, which is depending on the initial stress and precuring in between 29 N/mm^2 (σ_i = 15 N/mm^2, water cured specimens), 24 N/mm^2 (σ_i = 28 N/mm^2, water cured specimens) and 22 N/mm^2 (σ_i = 8 N/mm^2, sealed cured specimens), resp. After exceeding the maximum the restraint forces decrease due to strong dewatering and related creep processes. This holds for the temperature region 100°C to about 200°C. Then the strong drying period ends and the restraint forces again slightly increase.

Worth to mention, the effect of the initial stress σ_i on the development of the restraint forces vanishes with increasing temperature. Already at 100°C the effect of σ_i is almost negligible (comp. fig. 3 and 4); the respective curves of the water cured specimens loaded initially with 8 N/mm^2 respectively 15 N/mm^2 indicate in the temperature region 130°C ... 300°C almost identical stresses. Generally in this region the scattering of the data measured with different initial stresses is lower than the scattering in the temperature region 20° ...230°C measured with the three specimens under identical test conditions.

With the sealed cured specimens and the water cured specimens there is in the temperature region 120° ...160°C a relatively strong conformity observable, however, above 180°C the sealed cured specimens show distinctively higher restraint forces than the water cured specimens. It is supposed that this is due to the lower degree of hydration of the cement paste respectively the lower amount of fluid phase (comp. Diederichs, 1990).

The restraint forces of the sealed heated specimens (comp. figs. 6 and 7) in the initial heat-up phase (20°...80°C) hardly differ from the respective curves of the unsealed heated specimens. Also with the sealed specimens the effect of the initial stress on the development of the restraint forces decreases with increasing temperatures; above 160°C it is usually lower than the usual test scattering.

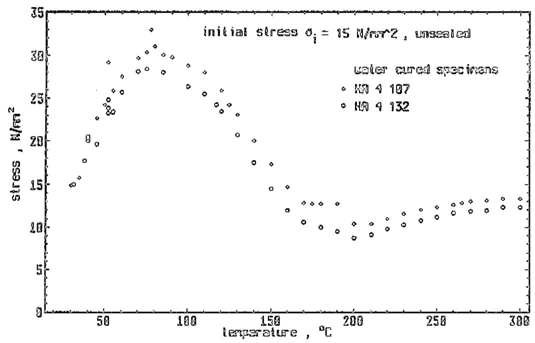

Fig. 3: Restraint forces with unsealed heated specimens

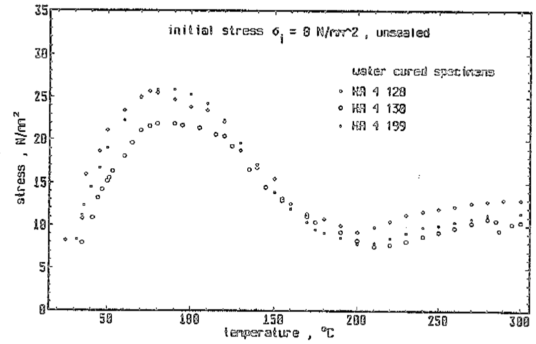

Fig. 4: Restraint forces with unsealed heated specimens

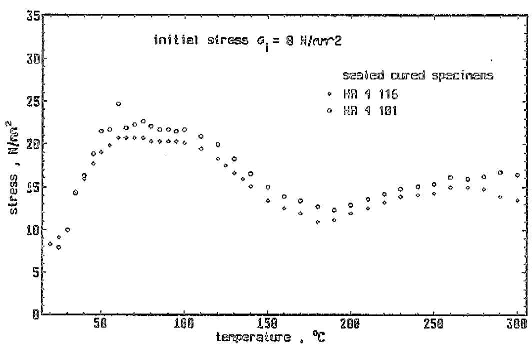

Fig. 5: Restraint forces with unsealed heated specimens

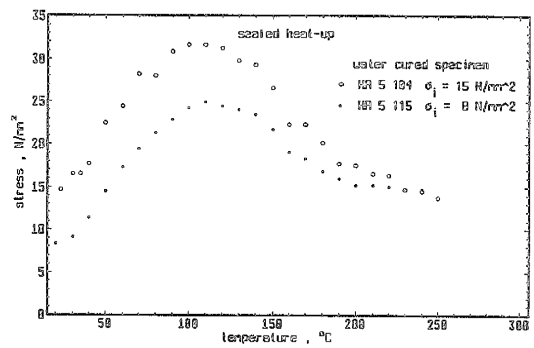

Fig. 6: Restrained forces with sealed heated specimens

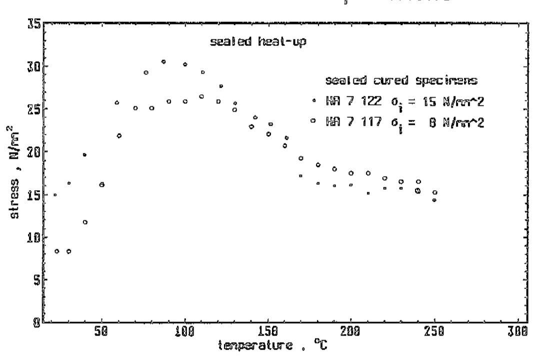

Fig. 7: Restrained forces with sealed heated specimens

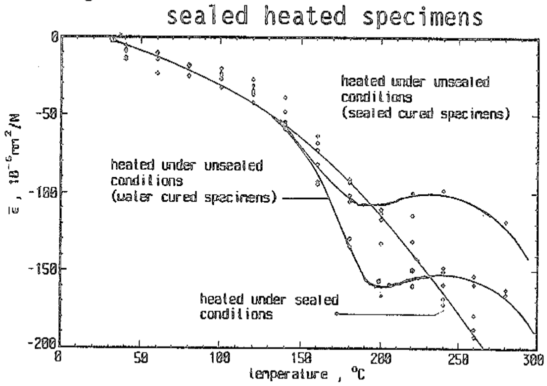

Fig. 8: Normalized transient strain $\bar{\varepsilon}(T)$ obtained from the restraint tests

Above 80°C there are appearing significant differences between unsealed and sealed specimens. The maximum restraint forces of the sealed heated specimens are first reached at about 110°C. They are also a little bit higher than with the unsealed heated specimens (30 N/mm² with σ_i= 15 N/mm²; resp. 26 N/mm² with σ_i = 8 N/mm²).

After exceeding the maxima the restraint forces of the sealed specimens decrease in the same manner like the unsealed specimens. The strong decrease, however, occurs first at ca. 135°C. Compared with unsealed specimens, it is shifted by about 35°C to higher temperatures. - After an initially strong decrease of the restraint forces their decrease slows down in the same way as it is observed with the unsealed specimens, but in the temperature region 120°...250°C the restraint forces of the sealed specimens are distinctably higher than the respective values of the unsealed heated specimens.

The influence of the hydration and curing conditions of the specimens appears to be remarkably smaller with the sealed heated specimens than with the unsealed heated specimens. With the sealed heating the sealed hydrated respectively cured specimens also show slightly higher restraint forces than the water cured specimen. This holds mainly for temperatures > 160°C.

Fig. 8 summarizes the measured data. There are indicated the specific transient creep functions $\bar{\epsilon}$ calculated according to a material model given by Diederichs et al. (1987) and Diederichs et al. (1989).

In this model the total deformation ϵ_{tot} is composed of three components:

$$\epsilon_{tot} = \epsilon_{th}(T) + \epsilon_{el}(\sigma) + \epsilon_{tr}(\sigma,T) \quad \text{respectively,} \qquad (1)$$

$$\epsilon_{tot} = \epsilon_{th}(T) + \frac{\sigma}{E(20°C)} + \sigma \cdot \bar{\epsilon}(T) \qquad (2)$$

The thermal expansion ϵ_{th} depends only on temperature and moisture, the normalized transient strain $\bar{\epsilon}$ on the temperature and presumedly on the load level. The modulus of elasticity E(20°C) is a constant; σ is the actual stress. $\bar{\epsilon}$ can be determined from results of transient creep tests.

The evaluation of a series of transient tests with various mixtures has yielded, that the concrete deformations may be predicted with sufficient accuracy by the equation (3); the measured load dependent transient strains are normalized to the actual stress σ as following

$$\bar{\epsilon} = (\epsilon_{tot} - \epsilon_{el}\ (\sigma) - \epsilon_{th})/\sigma \qquad (3)$$

With restraint tests the total deformation ϵ_{tot} is identical with the initial deformation $\epsilon_i = \sigma_i/E(20°C)$, this gives

$$\bar{\epsilon} = (\sigma_i/E(20°C) - \epsilon_{th})/\sigma - 1/E(20°C) \qquad (4)$$

For the calculations the different thermal expansions of sealed and unsealed heated specimens have been taken into account. The results show that the creep functions up to about 140°C are almost independent of the type of precuring and the moisture regime during heating. Above 140°C the normalized transient strain function splits into three different branches: The function of the sealed heated specimens further monotoneously runs with increasing rate. The functions of the unsealed heated specimens show at first a higher increase of the rate than the sealed specimens. But, after the strong dewatering reactions have ended, the transient strain function shows a more or less pronounced hold time period. A further increase of the values starts again at about 260°C.

Only with the unsealed heated specimens occurs a distinct difference concerning the transient behaviour of sealed cured and water cured specimens. The specimens which were sealed cured, and therefore having lower degree of hydration and water content, respectively, indicate remarkably lower transient strain values. The dryer the concrete the lower the transient strain.

SUMMARY

PCRV contains of certain areas where the hot concrete is restraint by the surrounding colder concrete regions. There we have no established concepts at hand to estimate the arising restraint stresses with sufficient accurracy. Therefore restraint tests were conducted to gather the needed reliable data for elaboration and confinement of a constitutive model.

The tests were performed with HTR-basalt concrete. Cylindrical specimens (diameter = 8 cm, length = 24 cm) were uniaxially loaded at ambient temperature with stresses of 8 N/mm^2 and 15 N/mm^2, resp. The respective initial deformation was measured and the specimens were heated under sustained (initial) deformation with constant heating rate (5 K/h) under sealed as well as under sealed conditions up to 300°C.

The tests yielded transient restraint forces data during heat up of sealed and unsealed specimens. These data have been evaluated by the aid of a materials model interlinking the restraint forces development and transient creep behaviour.

The tests showed that up to 100°C there is hardly a difference in restraint behaviour of sealed and unsealed specimens. But the higher thermal expansion of sealed specimens caused also higher restraint forces of sealed specimens in the temperature region 100°C to 250°C.

Furthermore, the evaluation of the test data showed that the unsealed and sealed heated specimen indicate up to 140°C the same transient strain value, but above 140°C marked differences occur, which are mainly caused by the differences in moisture migration.

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