Uniaxial Strength and Deformation of HTR–Concrete at High Temperature up to 600°C

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INTRODUCTION

In course of research and development of the PCRV prestressed concrete vessel of the HTR 500 high-temperature reactor comprehensive analyses concerning technology and thermomechanical behaviour of the concrete were performed (see Becker (1984)). 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, related to service and accident temperatures up to 300 °C, have already been published (see i. a. Schneider et al. (1983), Weber et al. (1985), Diederichs et al. (1987)).

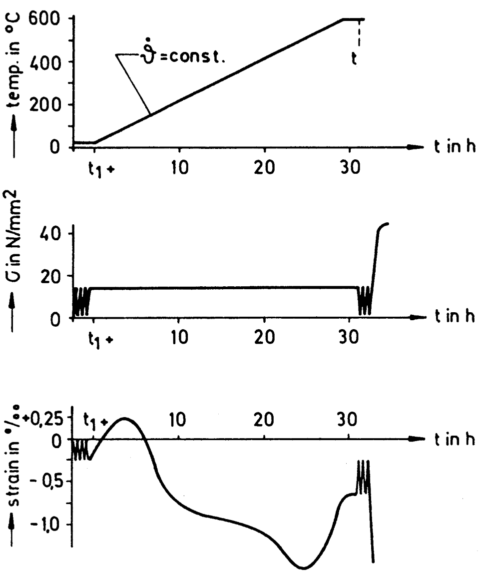
Advances in the safety analysis of the HTR-reactor as well as the development of the HTR-heating reactor have revealed the urgent need of data on the mechanical behaviour of concrete beyond the design accidents (abnormal service, basis accidents), during which the concrete may be subjected to more severe conditions, e. g. higher temperatures and simultaneous high mechanical stress. Therefore a series of tests with HTR-concrete made with Rhine gravel and basalt aggregates have been performed. The specimens were heated under sustained uniaxial stress of 15 N/mm^2 or unloaded up to temperatures of 400, 500 and 600 °C where they were loaded up to rupture to get information concerning strength, modulus of elasticity, transient creep and thermal expansion.

This paper reports briefly the main experimental results and the observed mechananical behaviour is discussed with regard to the microstructural changes of the concrete phases during thermal exposure.

EXPERIMENTAL

The specimens in the high temperature tests were cylinders with a diameter of 80 mm and a length of 240 mm. The mix proportions of the investigated HTR-concretes (Rhine gravel concrete and basalt concrete) as well as the data of the fresh and hardened concretes are already reported in detail by Weber et al. (1985) and Diederichs (1986).

The specimens were cast in iron moulds, demoulded after one day and stored under water for at least 90 days until testing. The testing procedure is given in Fig. 1. 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. After that they were loaded again with 15 N/mm^2. Under sustained load the specimens were then heated according to the heating program, designated temperature program I, II and III in Fig. 2, up to the selected test temperature (400 °C, 500 °C or 600 °C). The respective temperature was then kept constant for 2 h to homogenize the temperature field of the specimen. The modulus of elasticity was determined by unloading and loading the specimens three times. Subsequently the σ-ε-relationship was determined by loading the specimens up to failure using a constant strain rate of 3 o/oo per minute.



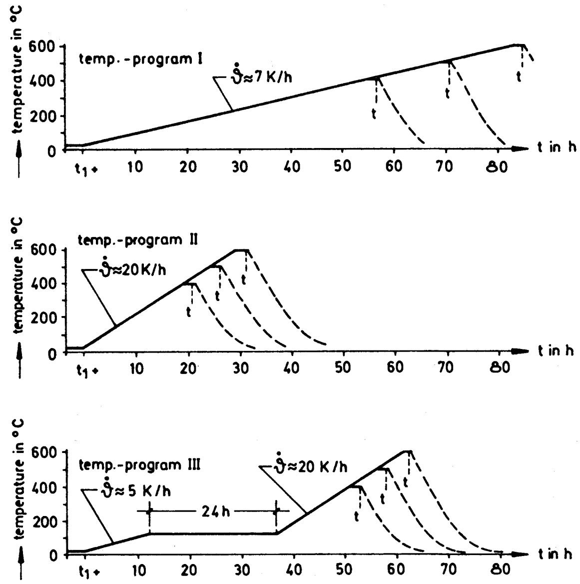


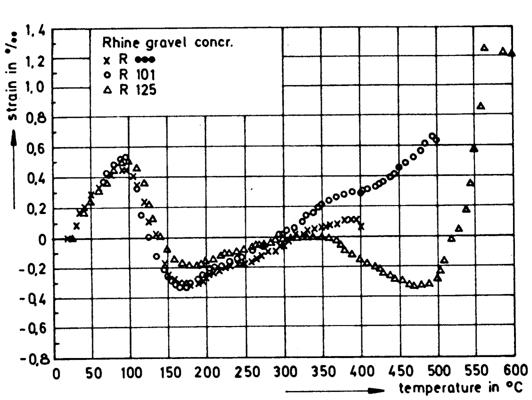
Fig. 1: Testing procedure for high temperature investigations

Fig. 2: Schematic representation of the different temperature programs

During the whole heating and testing procedure the concrete deformation was continuously recorded. Besides the mentioned tests unloaded specimens were heated according to the temperature program I and III to determine the thermal expansion.

RESULTS and DISCUSSION

The total strains versus surface temperature of the specimen of the Rhine gravel concrete measured during heating are given in Figs. 3, 4 and 5. In these figures the total strain of 0 o/oo at room temperature means that the initial elastic strain caused by loading with σ_o = 15 N/mm² is omitted.



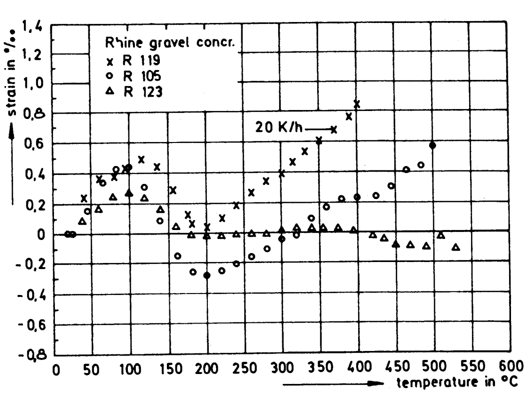


Fig. 3: Total strain of Rhine gravel concrete during heating (temperature program I - low heating rate)

Fig.4: Total strain of Rhine gravel concrete during heating (temperature program II - high heating rate)

During the heating at first all specimens show expansion. Thereafter when surface temperatures of 90 °C ... 100 °C are exceeded, the expansion reaches its maximum and shortening starts inspite of further temperature rise.

With the continously heated specimens (comp. Figs. 3 and 4), the shortening caused by shrinkage and transient creep ends at temperatures between 175 °C and 200 °C and the specimens expand again. At nearly 300 °C the specimens reach their initial length, i. e., the shortening due to shrinkage and transient creep of the binding phase are compensated by the thermal expansion of the aggregates. Above 300 °C the rate of expansion increases continuously and reaches a maximum at 570 °C in consequence of the spontaneous quarz expansion ($\alpha \rightarrow \beta$-transformation). Thereafter, with increasing temperatures, specimens expand hardly further because strong dehydration - and beyond 700 °C sintering - lead to forced shrinkage of the hardened cement paste.

After the end of the hold time period the stepwise heated specimens reveal during heating at first only negligible small transient creep rates (see Fig. 5). After a temperature increase of 80 °C, which means above 200 °C the deformation curves fit nearly identical in with the curves obtained during continuous heating. This leads to the conclusion that after a temperature rise of 80 °C the influence of the preceding thermo-mechanical history becomes negligible for the further high temperatur behaviour of concrete.

The thermal expansions of Rhine gravel concrete and basalt concrete are nearly identical up to 160 °C (see Fig. 6). First at higher temperatures the lower thermal expansion of the basalt aggregates becomes obvious.

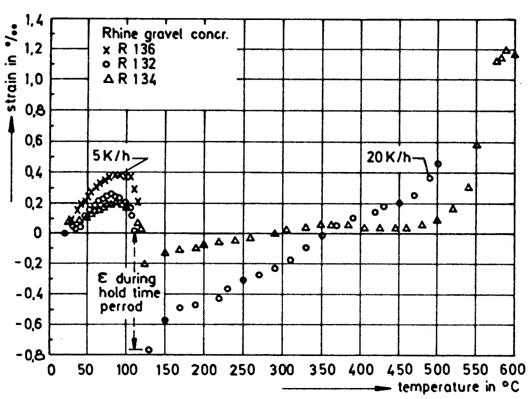


Fig. 5: Total strain of Rhine gravel concrete during heating (temperature program III - stepwise heating)

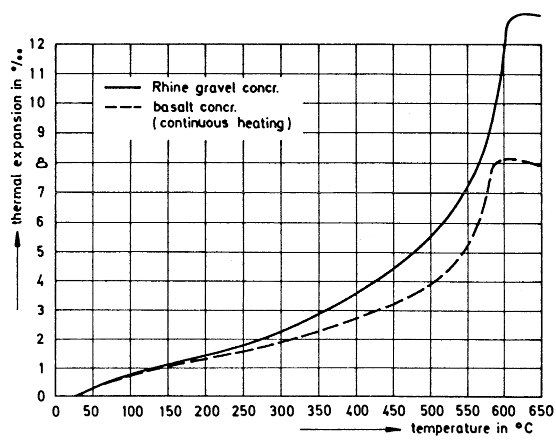


Fig. 6: Thermal expansion of Rhine gravel concrete and basalt concrete during heating (temperature program I)

The normalized transient strain (ε_{tr} (σ,T)) of basalt concrete and Rhine gravel concrete calculated according to the following equation (comp. Khoury et al. (1987) and Diederichs (1986 and 1989):

$$\varepsilon_{tr} (\sigma, T) = (\varepsilon_{tot} - \sigma/E(20\ °C) - \varepsilon_{th} (T))/\sigma,$$

where ε_{tot} = total deformation, E (20 °C) = modulus of elasticity, ε_{th} (T) = thermal expansion and σ = compressive stress, are given in Fig. 7. It indicates, that both concretes reveal almost identical normalized transient strains. This can be attributed to the same contents of the "fluid phase" (cement paste) in both concretes.

The σ-ε-relationships measured with specimens loaded during heating are shown in Figs. 8 and 9. It can be seen, that at the same temperature the σ-ε-curves obtained with three different specimens are very similiar.

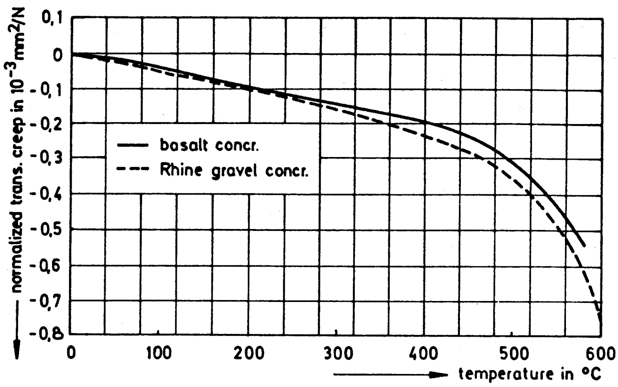


Fig. 7: Normalized transient strain functions of basalt concrete and Rhine gravel concrete

Worth to mention, the ultimate strain (strain at max. stress) is at high temperatures about 1.6 - 2.2 o/oo and a little bit lower than at ambient temperature. On the other hand, the ultimate strains of the unloaded specimens (see Fig. 10) are more than 3 times higher than those of the loaded specimens. Simultaneously, the loss of strength of unloaded specimens markedly exceeds that of loaded specimens. - The same behaviour as described above has been found with basalt concrete.

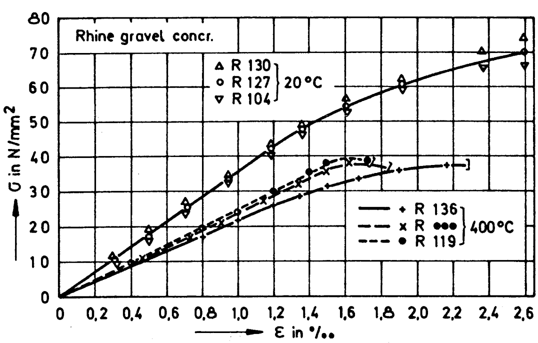


Fig. 8: σ-ε-relationships of Rhine gravel concrete determined at 20 °C and 400 °C (loaded during heating)

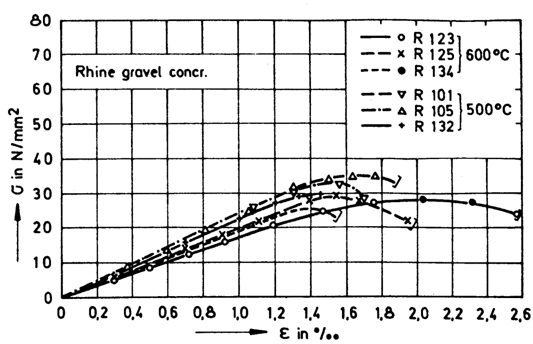


Fig. 9: σ-ε-relationships of loaded Rhine gravel concrete determined at 500 °C and 600 °C,

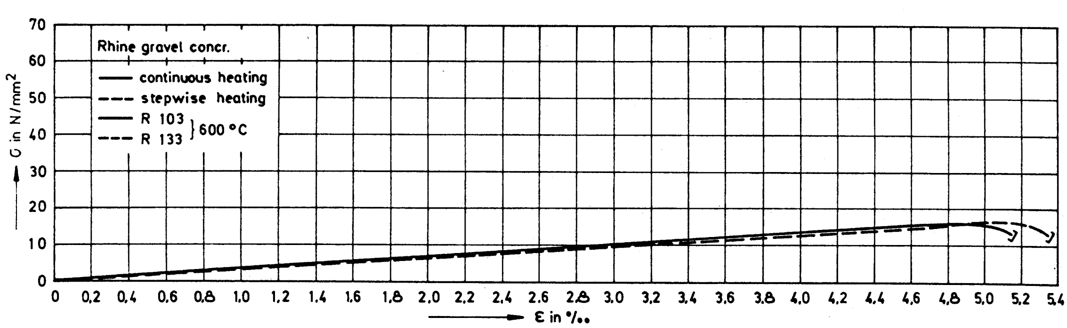


Fig. 10: σ-ε-relationships of non-loaded Rhine gravel concrete determined at 600 °C.

The measured compressive strength and modulus of elasticity data of both concretes are compiled in Table 1. The strength of the basalt concrete specimens, heated under mechanical load, has at 400 °C reduced to 58 % of the original strength; that of Rhine gravel concrete respectively to 55 %. At 600 °C, the basalt concrete suffers a strength loss of only 52 %, while the Rhine gravel concrete maintains only 40 % of the original strength. But, generally both concretes behave similiarly and the loss of strength and reduction of modulus of elasticity are of the same order of magnitude. Furthermore, it can be seen that strength reduction in general is highest with stepwise heated specimens and lowest if heating was performed with low heating rate. However, the temperature regime has only a marginal influence. The biggest effect on reduction of strength and modulus of elasticity has the load level during thermal exposure. - The strength and elastic modulus reduction of the unloaded specimens exceeds that of loaded specimens by a factor of 2 and more.

Table 1. Compressive Strength and Elastic Modulus of Rhine Gravel Concrete and Basalt Concrete at High Temperatures

specimen nr.	temperature, °C	temperature programm	Rhine Gravel Concrete		Basalt Concrete	
			compressive strength, %	elastic modulus, %	compressive strength, %	elastic modulus, %
1 2 3	20 20	- - -	105.2 95.0 99.6	97.4 114.7 87.9	100.2 99.5 100.2	92.9 110.7 96.2
			$\bar{x}$= 100.0*)	100.0**)	100.0+)	100.0++)
4 5 6	400	I II III	53.7 57.1 53.5	64.9 56.4 61.2	59.1 58.2 56.3	55.8 56.7 55.1
			$\bar{x}$ = 54.7	60.7	57.8	55.8
7 8 9	500	I II III	46.7 49.5 41.6	49.3 40.8 48.6	54.4 52.5 50.6	57.1 54.5 60.5
			$\bar{x}$ = 46.0	46.2	52.5	57.4
10 11 12	600	I II III	41.6 39.6 39.6	44.0 33.3 44.0	48.1 47.3 46.1	53.3 47.8 46.2
			$\bar{x}$ = 39.3	40.3	47.2	49.1
13 14	600	ε_{th}, I ε_{th}, III	24.1 22.9	12.1 13.9	25.6 26.7	13.2 8.7

*) 100 % ≙ 70.7 N/mm², **) 100 % ≙ 41.2 kN/mm²

+) 100 % ≙ 63.6 N/mm², ++) 100 % ≙ 44.8 kN/mm²

CONCLUSIONS

Thermal exposure leads to a significant loss of strength of concretes, which is higher with the Rhine gravel concrete than with the basalt concrete. This may be attributed to the lower thermal expansion of the basaltic coarse aggregates, which leads to less microcracks in the fine mortar matrix. At 600 °C the basalt concrete suffers a strength loss of 52 % while the Rhine gravel looses over 60 % of its original strength. Even with the measured minimum strengths at 600 °C of 30,0 MPa (basalt concrete) and 28 MPa (Rhine gravel concrete) the integrity of the PCRV is ensured.

Up to 600 °C the transient creep deformations of both types of concrete are nearly identically. This may be ascribed to the same content of hydrated cement in both concretes. The main difference in the deformation behaviour of the two concretes was found in the thermal expansions, which depends mainly on the thermal expansion of the coarse aggregates. Therefore, above 200 °C the thermal expansion of Rhine gravel concrete clearly surpasses the thermal expansion of basalt concrete.

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