Effects of Long-Term Thermal Exposure on the Behaviour of HTR-Concrete

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Abstract

The optimum design of the prestressed concrete reactor vessel (PCRV) for the high-temperature reactor (HTR) requires a detailed knowledge concerning the mechanical behaviour of the structural concrete considered to be used (HTR-concretes developed so far: a basalt concrete and a Rhine gravel concrete). In this connection an extensive experimental program has been conducted to study the residual strength and the residual modulus of elasticity of the HTR-concretes. Therefore HTR-concrete specimens (cylinders: diameter = 15 cm, length = 30 cm) were subjected - according to the expected service and accident conditions in the vessel - to 70, 120 and 200 °C under sealed as well as under unsealed conditions for different periods of time (1, 7, 28, 90 and 360 d, resp.). For 300 °C only a 1 day and a 7 day exposure under unsealed conditions was intended. In the report the obtained results are given and discussed.

1. Introduction

These investigations present only one part of an extensive research and development program for the PCRV for high-temperature reactors. The preparation of this program, the attendance of the tests and the subsequent evaluation was performed by Hochtemperatur-Reaktorbau (HRB). Within the scope of the concrete R&D-program comprehensive experimental investigations were performed. Requirements to the fresh and hardened concrete, resp., were: Low heat of hydration, good workability and pumpability, nominal strength $f'_{C90d} \geq 51$ N/mm² and low reduction of the modulus of elasticity also after a thermal exposure up to 250 °C as well as low creep, shrinkage and thermal expansion.

First investigations were related to the development of the respective concrete mixtures. From all concrete mixtures investigated, two types of concretes fulfilled the main requirements best: a basalt concrete indicates very advantageous material properties at high temperatures and a Rhine gravel concrete shows a more suitable workability /1/.

With both of these concrete investigations concerning the basic material properties were performed. Also supplementary technological investigations were conducted to ensure an economic engineering design and construction of the PCRV /2/. Further, detailed high-temperature investigations were performed. These investigations covered mainly the mechanical properties of
the concrete under thermal and hygroscopic conditions, which are expected to occur in the PCRV due to the design and service conditions /3, 4/. The following report deals with the effects of long term thermal exposure on strength and deformation behaviour of basalt and Rhine river gravel concrete.

2. Experimental Investigations

The tests were performed at the Institut für Baustoffe, Massivbau und Brandschutz, Technical University of Braunschweig. The specimens (cylinders: diameter = 15 cm, length = 30 cm) were exposed to elevated temperatures under sealed as well as under unsealed conditions to cover the two extreme moisture regimes of the concrete in the vessel: completely water-saturated concrete regions and dried concrete regions. "Sealing" was provided by heating the specimens in water vapour-tight steel casings. The "unsealed" specimens could freely evaporate the water during heating and tempering in an oven. The weight loss, the strength and the modulus of elasticity were determined for the respective specimens after sealed and unsealed storage under the above-mentioned long term thermal conditions.

For all tests the heating and cooling rates were ca. 5 K/h, measured at the surface of the specimens. The determination of the strength, the modulus of elasticity and the weight loss (difference between the original weight and the weight after thermal exposure) were determined for each test parameter combination using 3 specimens, this results in more than 100 single tests for each type of concrete. The modulus of elasticity tests were performed and evaluated according to DIN 1048. That means, that the specimens were exposed to 10 loading-unloading cycles with max. stresses of 1/3 of the expected ultimate stress and minimum stresses of ca. 0.5 N/mm². The 10th loading response was used to calculate the modulus of elasticity as second modulus.

3. Results

3.1 Elastic Behaviour and Weight Loss

Fig. 1 indicates the stress-strain curves of basalt concrete obtained by the first and the 10th loading cycle. In addition, the stress-strain response of a thermally unstressed reference specimen is shown (20 °C specimen). For the reference specimens of basalt concrete a modulus of elasticity (mean value of 9 specimens from 3 concrete batches) of 45.9 kN/mm² has been determined.

As shown in Fig. 1, there is hardly a difference in the elastic modulus as well as in the residual strain after unloading between the 20 °C reference specimen and the 70 °C sealed stored specimen. On the contrary, the 70 °C unsealed stored specimen already indicates a markedly stronger inclination of the stress-strain curves. Another significant feature is the difference of the shape of curves representing the first and 10th loading cycle. The residual deformation after unloading is much more pronounced compared to the residual shortenings of the 20 °C specimen.

The inclinations of the stress-strain curves of sealed specimens exposed to 120 °C and to 200 °C as well as the residual shortenings show a further small increase compared to the 70 °C specimens, but this increase is much smaller than observed with the respective unsealed
specimens. For the 120 °C, 200 °C and 300 °C unsealed specimens the hysteresis between first loading and first unloading increases with increasing test temperature. The residual shortenings after the first unloading - e.g. for the 300 °C specimens - are in the order of 0.5%.

It is worth mentioning that due to the significant non-linear elastic behaviour of the unsealed stored specimens, the modulus of elasticity depends strongly on its definition, e.g., in case of secant modulus mainly on the selected minimum and maximum stresses.

The reasons for the strong decrease of the elastic moduli of the unsealed specimens are mainly dewatering reactions due to heating, whereby the cement paste shrinks and simultaneously the aggregates expand. Due to these thermal incompatibilities micro-cracking occurs, especially in the contact zone between aggregates and cement paste /5/. Partly, these cracks are closed during the first loading which causes the hysteresis between 1st loading and 1st unloading. The fact, that after drying and shrinkage the cement paste is not flushed with the aggregates anymore, but the aggregates are partly only in point contact with the paste, causes the non-linear elastic behaviour. In this context it should be mentioned, that beside the moisture content especially the load level during heating has a strong influence on the deformation behaviour of concrete at high temperatures /6/. It can, however, be clearly seen in Fig. 2, that the loss of moisture and the related shrinkage of the cement paste are in close connection with the decrease of the elastic modulus. It indicates beside the dependence of the elastic modulus on storage temperature and storage duration also the related loss of moisture.

For the sealed stored specimens, also differences of the thermal expansions of the cement paste and the aggregates are responsible for the decrease of the elastic modulus /7/. But, furthermore, also hydrothermal reactions accompanied by formation and reformation of CSH-phases are leading to a coarsening of the internal structure and reduction of the elastic modulus of the original cement gel. This applies especially to higher temperatures (200 °C) (see Fig. 3). With storage temperatures of 70 °C and 120 °C, the initial decrease in the modulus of elasticity (storage duration 1 d) is possibly compensated respectively overcompensated by a thermally activated further hydration of unhydrated cement. Simultaneously hydrothermal reactions at these relatively low temperatures lead to extremely stable new phases in the cement paste /3/.

For the Rhine gravel concrete a reference modulus of elasticity of 32.9 kN/mm² (mean value of 9 specimens from 3 batches after 90 d storage under water at 20 °C) has been estimated. After thermal treatment the Rhine gravel concrete indicated comparative stress-strain responses as obtained with the basalt concrete (comp. Fig. 1). But, in general the relative decrease of the elastic moduli due to thermal treatment (Em(T)/Em(20°C) is lower for the Rhine gravel concrete than for the basalt concrete (compare Fig. 2 and Fig. 3 with Fig. 4, resp.), however, in nearly all cases the absolute values Em(T) are somewhat higher for the basalt concrete.

3.2 Strength Behaviour

The strength behaviour of basalt and Rhine gravel concrete was determined as a residual strength of specimens, which were unloaded during tempering.
After tempering at 70 °C under sealed as well as under unsealed conditions in the course of the storage up to 28 d the basalt concrete indicated a strength increase. After 90 d storage the strength of the unsealed specimens is reduced to a minor extent below the original strength, while the sealed stored specimens indicate a strength increase of nearly 10 % (Fig. 5). Essentially, the Rhine gravel concrete shows the same behaviour. The main reason for the strength increase seems to be afterhardening of the cement paste at elevated temperatures.

At 120 °C the unsealed stored basalt concrete shows a slightly lower strength compared to the 70 °C-specimens. Obviously, already structural damage occurs, caused by shrinkage of the cement paste due to its drying, which in turn affects the concrete strength. For the Rhine gravel concrete the structural damage caused by drying seems to be overcompensated by hardening of the cement paste matrix due to drying /8/.

For the 120 °C sealed cured specimens initially structural damage occurs, which is relatively strong in case of basalt concrete due to the relatively large differences between the thermal expansions of water-saturated paste and the basalt aggregates. In the course of further storage a structural recovery occurs due to hydrothermal reactions, which results in an increase of strength.

At 200 °C and unsealed storage, the strengths are slightly decreased compared with the respective values at 70 and 120 °C, with the basalt as well as with the Rhine gravel concrete. The main reason for this behaviour seems to be increased shortenings of the cement paste due to shrinkage. For the Rhine gravel sealing leads to a strong increase of strength, which increases with prolonged periods of storage at 200 °C.

For basalt as well as Rhine gravel concrete unsealed curing at 300 °C leads to a further decrease of strength. The decrease of strength in either concrete amounts to ca. 20 %. Conclusively it can be stated, that with one exception (Rhine gravel concrete stored for 7 d at 300 °C) independently of the curing conditions, all specimens showed higher strengths than the required nominal strength of $f_{c,90N} = 51$ N/mm².

4. Conclusion

From the investigations conducted so far it can be concluded that the strength and the deformation behaviour of HTR-concrete is determined not only by the prevailing temperatures but also significantly by the moisture regime.

Up to 120 °C (basalt concrete) and up to 200 °C (Rhine gravel concrete), respectively, sealed specimens show only a very small reduction of the elastic modulus, nearly irrespective of the exposure time. On the other hand, unsealed specimens show a significant reduction of the residual modulus of elasticity which is strongly related to the loss of moisture.

The loss of strength of unsealed HTR-concretes (basalt as well as Rhine gravel concrete) is negligible as far as temperatures up to 200 °C are concerned. In some cases, even a gain of strength was observed. But, at 300 °C, a loss of strength in the order of 20 % was observed, irrespective of the type of concrete.
Sealed exposure to a temperature of 70 °C leads to a gain of strength for both concretes. At higher temperatures the behaviour is different. In general, the Rhine gravel concrete shows an increase in strength with the exposure duration. On the other hand, the basalt concrete indicates at first a loss of strength, but due to hydrothermal reactions a recovery of strength with the duration of thermal exposure.

The current investigations could focus only the two extreme cases - freely evaporating concrete and completely water-saturated concrete. The real moisture regime during service conditions - which according to the present state of knowledge can be estimated only by experiments (liner simulation model) - is certainly to be found in between those two extreme cases. Only if the respective verified data concerning the moisture regime are at hand, the deformation and strength behaviour of the reactor concrete can realistically be evaluated under service conditions as well as in accident conditions.

5. References


Fig. 1: Stress-strain responses of basalt concrete tested at ambient temperature after storage at elevated temperature for 7d under sealed respectively unsealed conditions.

Fig. 2: Modulus of elasticity and loss of moisture of basalt concrete stored under unsealed conditions.

Fig. 3: Modulus of elasticity of basalt concrete stored under sealed conditions.

Fig. 4: Modulus of elasticity and loss of moisture of gravel concrete stored under (a) unsealed and (b) sealed conditions.

Fig. 5: Strength of basalt concrete stored under (a) unsealed and (b) sealed conditions.