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Material Properties of High Strength Concrete at Elevated Temperatures

Propriétés d'un béton à haute résistance sous des températures élevées

Materialeigenschaften von hochfestem Beton bei hohen Temperaturen

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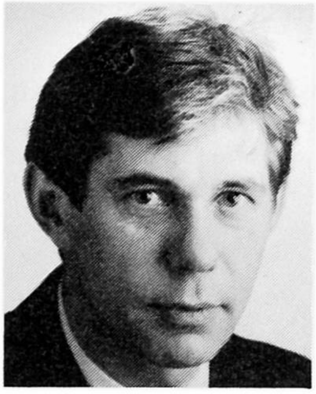

SUMMARY
By the use of high strength concretes the economy and safety of the structures in energy technology as well as in conventional house-building can be enhanced considerably. This involves a knowledge of high temperature behaviour of these concretes because the structures may – either in normal service or under catastrophic conditions – be subjected to high temperatures, and they must be correspondingly designed. This paper reports results of experimental investigations of high temperature behaviour of three high strength concretes.

RÉSUMÉ
De par l'installation d'un béton à haute résistance comme matériau de construction, il est possible d'améliorer la rentabilité et la sécurité de constructions et d'éléments de construction dans le domaine de la technique de l'énergie et celui du bâtiment. Ceci suppose une bonne connaissance des propriétés à hautes températures, puisque les éléments de construction sont exposés à des températures élevées, soit en service normal, soit lors de catastrophes, et qu'ils doivent être dimensionnés en conséquence. Les résultats des essais de matériaux sont présentés.

ZUSAMMENFASSUNG
Durch Einsatz von hochfestem Beton als Konstruktionswerkstoff kann die Wirtschaftlichkeit und Sicherheit von Bauwerken und Bauteilen der Energietechnik und des normalen Hochbaus erheblich verbessert werden. Dies setzt die Kenntnis der Hochtemperatureigenschaften voraus, weil die Bauteile entweder im Normalbetrieb oder bei Katastrophen (z. B. Feuer) hohen Temperaturen ausgesetzt sind und entsprechend dimensioniert werden müssen. Ergebnisse von umfangreichen Materialuntersuchungen werden vorgestellt.

1. INTRODUCTION

The application of high strength concretes in off-shore-platforms and prestressed reactor pressure vessels arouses special interest because of the increased economy and safety of the structures. Besides, the use of high-strength concretes can be increased also in normal structures, cast in situ as well as in prefabricated elements - like hollow core slabs and composite columns. In all the cases the high temperature properties of the concrete in question must be known as the structures may be subjected to high thermal loads either in their service or catastrophic conditions (reactor accident, fire etc.) and must be correspondingly designed.

Up to now our knowledge of the high temperature behaviour of concrete is restricted to normal strength concretes (K15...K50). Extending the known data by linear extrapolation to cover also high strength concretes is not necessarily relevant, because due to their special composition and microstructure high strength concretes may be subjected to high temperature phenomena up to now not perceived (destructive spalling, exceptionally strong destruction of cement matrix due to thermal exposure etc.).

This paper presents the results of the experimental investigations carried out on three high strength concretes based on different combinations of binder and superplasticizers (compressive strengths - 100 mm cubes - at the age of 90 d: 101...112 MPa).

2. EXPERIMENTAL

2.1 Materials

Three different high strength concretes (HSC) were investigated experimentally. The concretes differed in the composition of the binder (blast furnace slag cement, series Tr; Portland cement with silica fume, series Si; Portland cement with class F fly ash, series Lt). The type of aggregates was same in all three concretes and the grading of the aggregates was similar in Si and Lt concretes and slightly different in Tr concrete. The mix proportions and some concrete data are given in Table 1, where also the respective data for a normal strength concrete (OPC /3/) are given. The aggregate of the high strength concretes comprised granite-based sand and crushed diabase, whereas the OPC concrete contained mainly greywacke, sandstone, quartz and quartzite as coarse aggregates. The preparation and conditioning of the specimens (cubes 100x100x100 mm^3 for strength tests and cylinders 80 mm in diameter and 300 mm in length for high temperature tests) until testing are thoroughly reported in /4, 5 and 6/.

2.2 Test methods

To determine the strength and deformation behaviour at high temperatures stress-strain, transient creep and restraint tests were performed.

For the σ-ε-experiments the specimens were heated without external load in a special testing machine with a furnace using a heating rate of 2 K/min up to the desired temperatures. After homogenizing for 2 hours at the maximum temperature σ-ε-tests were performed with a constant strain rate of about 0.5 ‰/min.

To get information about the transient creep the specimens were loaded with a certain load level α ($\alpha = \sigma / \sigma_{ult}$, where σ_{ult} is the compressive strength at 20 °C) at ambient temperature and heated under constant load with constant heating rate (2 K/min) until failure. Simultaneously the total deformation and the surface temperature were measured. Total deformation with α = 0 represents thermal expansion.

Concrete series	Si	Lt	Tr	OPC
Cement type	P40/91	P40/7	M40/91	P40/91
- content (kg/m^3)	530	472	530	418
Additional binder	Silica	Fly ash	-	-
- content (kg/m^3)	53	157	-	-
Water content	129.2	147.0	145.0	188.0
Superplasticizer	Scancem	Scancem	Conflow	-
- dosage (kg/m^3)	14.6	15.7	15.0	-
Aggregate content (kg/m^3)	1876	1729	2002	1754
Water/binder ratio	0.26	0.27	0.30	0.45
Density (kg/m^3)	2648	2594	2654	2390
Cube strength (MPa)				
- 28 d	114.4	87.3	91.4	48.0
- 90 d	100.8	106.9	111.9	36.0
Cylinder strength (MPa)				
- > 90 d	106.6	91.8	84.5	32.9

Table 1 Mix proportions and concrete data.

To measure the development of restraint forces the specimens were loaded at ambient temperature, the initial load levels applied were 15, 30 and 45 % of σ_{ult}(20 °C). The measured strain was kept constant during heating (heating rate 2 K/min) and the imposed force as well as the temperature of the specimen were measured.

2.3 Test results

Fig. 1 shows the measured σ-ε-relationships of the high strength Lt concrete at elevated temperatures. Quite similar curves were obtained also for the other HS-concretes. They differ distinctly from those of normal strength concrete (OS-concrete) (Fig. 2). In general, the failure of HS-concrete is more brittle than that of OS-concrete. HS-concretes show already at 150 °C a very distinct loss of strength, about 30 %, whereas OS-concrete up to a temperature of 350 °C indicates even slight increase of strength (Fig. 3). Although the modulus of elasticity of OS-concrete at 20 °C is much lower than those of the HS-concretes, its relative decrease is stronger in the whole temperature range (Fig. 4).

Fig. 5 shows the total deformation of Si- and OPC-concrete measured during heating. Because of the smaller binder content and the higher thermal expansion of the coarse aggregate in OS-concrete also the thermal expansion of the OS-concrete is distinctly higher than that of the HS-concrete. If the specimens are heated under load the thermal expansion is much lower. With a load level of 20 % of σ_{ult}(20 °C) the HS-concretes show nearly no expansion. With load level of 60 % of σ_{ult}(20 °C) heated specimens of Si and Lt concretes failed already soon after exceeding 100 °C, whereas the specimens of series Tr maintained their load bearing capacity still with a load level of 70 % up to 110 °C and the specimens of series OPC with load level of 60 % even up to 450 °C.

The thermal expansions of the high strength concretes differ only slightly; also the total deformations are almost similar. This was to be expected as the binder content of the HS-concretes differed only marginally. The OS-concrete (OPC)

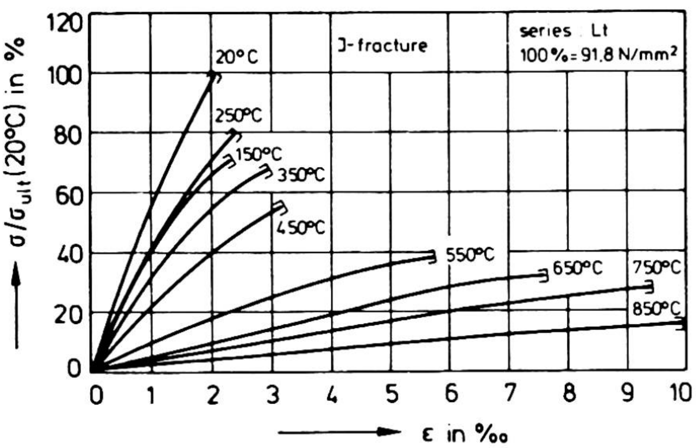

Fig. 1. Stress-strain relationships of high-strength concrete made with fly ash and Portland cement.

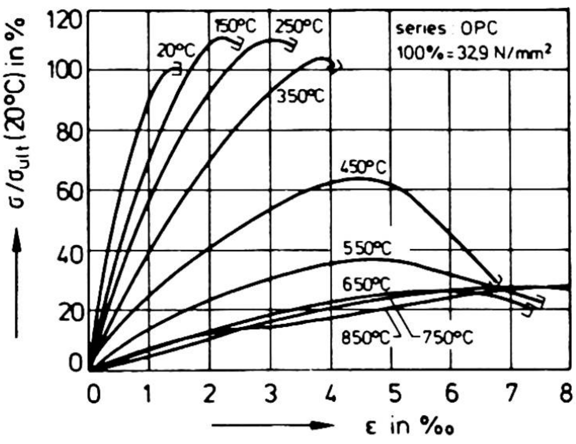

Fig. 2. Stress-strain relationships of Ordinary Portland cement concrete.

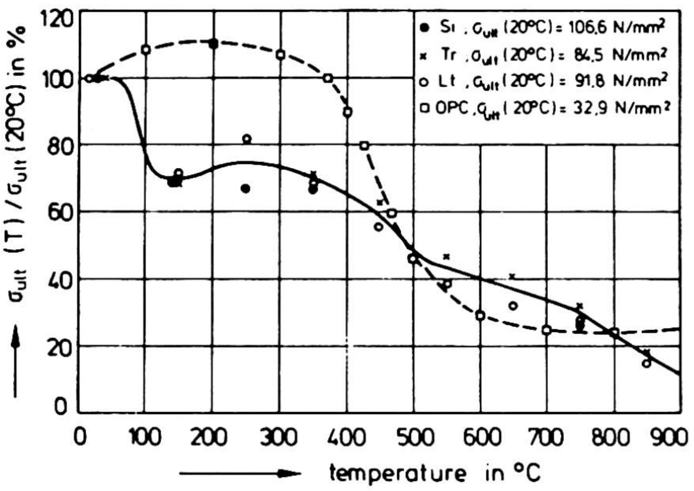

Fig. 3. Compressive strength of various high-strength and a normal strength concretes.

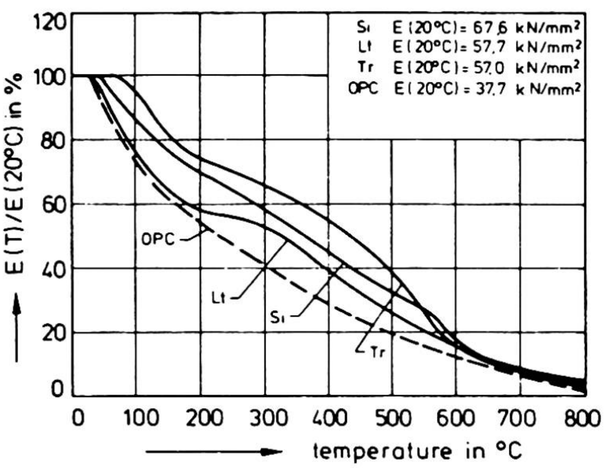

Fig.4. Modulus of elasticity of various high-strength and a normal concretes concrete.

contains considerably less binder and shows also correspondingly lower transient creep.

The development of restraint forces (Fig. 6) is mainly determined by the temperature dependence of the modulus of elasticity, thermal expansion and creep. Because of the likeness of the corresponding data for the series Si, Lt and Tr also the developing restraint forces are of the same magnitude. The slightly lower creep of Tr concrete at temperatures above 200 °C results in higher restraint forces especially in that temperature region. As expected, the OS-concrete shows higher restraint forces than the HS-concretes.

Destructive spalling occurred in no specimen heated with a heating rate of 2 K/min, like reported by Hertz /2/. Some cylindrical specimens under load were heated with a maximum heating rate within reach of the furnace (max. 32 K/min measured on the surface of the specimen). In some cases, however independent of the load level, slight spalling occurred. With bigger specimens (prisms 100x100x400 mm^3) also loaded and heated with the maximum heating rate spalling occurred in all specimens (Si, Lt and Tr); in the especially dense concretes (Si and Lt) it caused failure of the specimen. It can be concluded that besides the

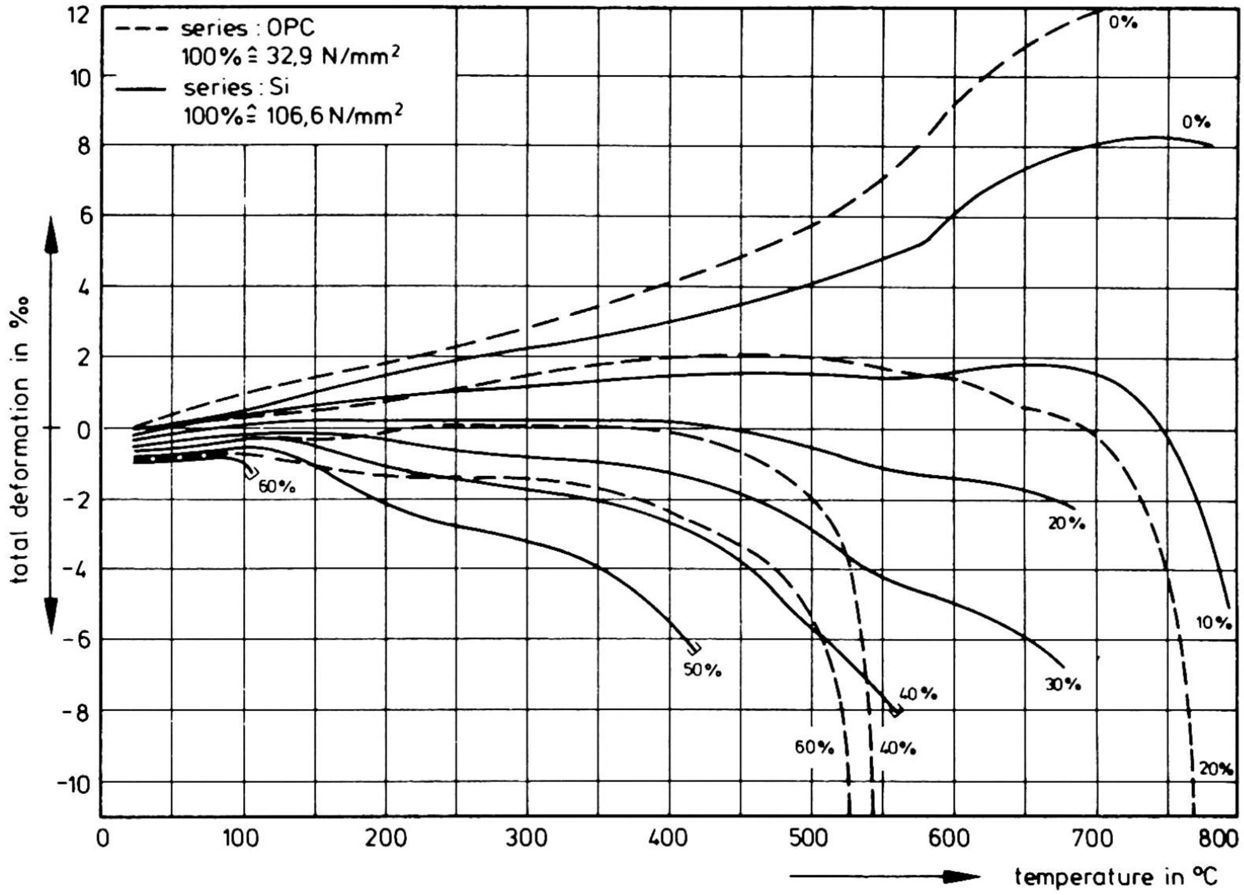

Fig. 5. Total deformation of loaded high-strength and normal strength concrete during heating.

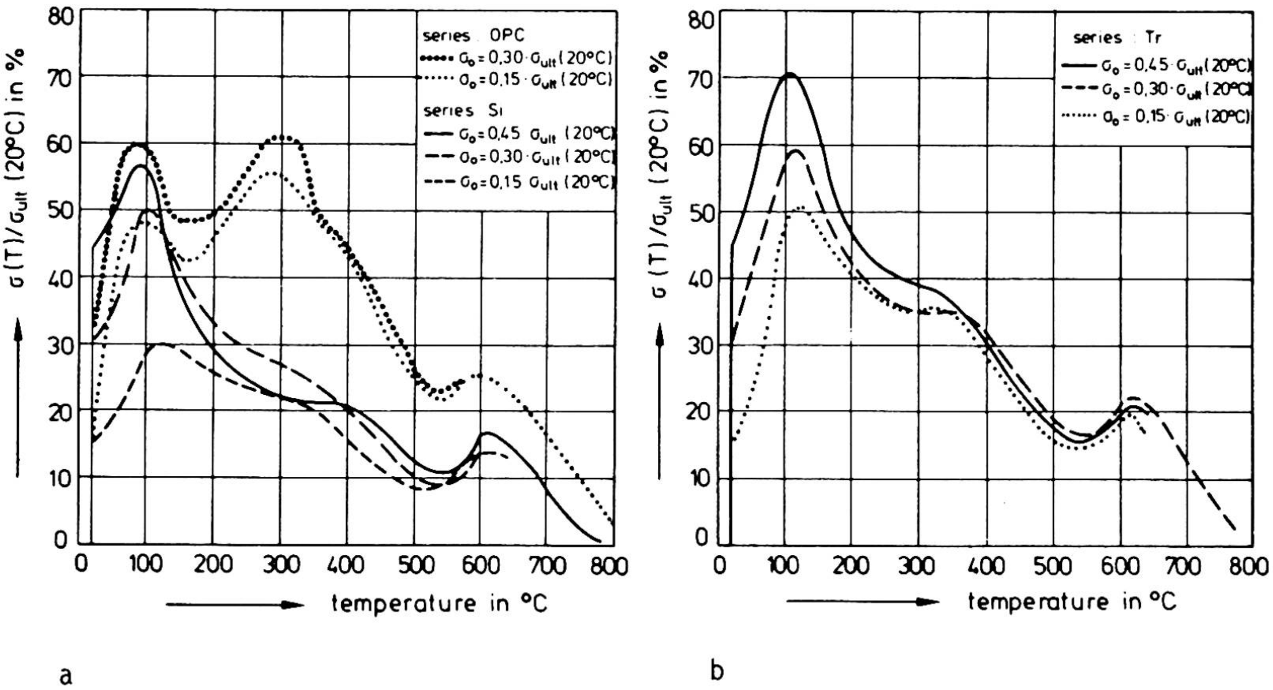

Fig. 6. Restraint forces of high-strength Si- (a) and Tr- (b) concretes and a normal strength concrete (a).

heating rate and the density of the concrete also the dimensions and the shape of the member are decisive with regard to destructive spalling.

3. CONCLUSIONS

To summarize, the high strength concrete, especially in the temperature region from 100 °C to 350 °C, show a stronger loss of strength than normal strength concrete. This is caused by temperature dependent destruction of cement paste. Its influence on the strength of high strength concretes is bigger than on that of normal strength concrete, because the cement paste matrix of high strength concrete must carry higher loads than in normal strength concrete (more homogeneous stress distribution between the aggregate and cement paste). Because the cement paste of high strength concrete is essentially denser compared with that of normal strength concrete it dries also at elevated temperatures relatively slow and the so called drying hardening causing mainly the increase of strength in normal strength concrete between 150 and 350 °C does not happen in high strength concrete. Besides, considering the structures exposed to high thermal loads (e.g. fire) higher risk of spalling must be taken into account.

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