EFFECT OF STRENGTH ON FIRE BEHAVIOUR OF CONCRETE

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ABSTRACT

The use of high strength concretes enhances the economy of structures, but this involves also a knowledge of their high temperature behaviour because the structures may be subjected to high temperatures (e.g. fire) and they must be correspondingly designed.

High temperature behaviour of different high and ultra high strength concretes has been investigated. Studies comprised mechanical properties and the chemical and physical background of their alteration due to heating. The high strength concretes showed a stronger loss of strength and a higher risk of spalling than normal strength concretes.

Key-words: Fire, High strength concrete.

1. INTRODUCTION

In recent years the development in concrete technology has made it possible to double - even triple - the compressive strength of concrete even applying customary production methods. Traditionally the structural regulations and codes have included the concretes with compressive strength of 15 - 60 MPa. The use of high strength (HS-) concretes requires knowledge of their high temperature behaviour because the structures may - either in normal service or under catastrophic conditions - be subjected to high temperatures and they must be correspondingly designed.

The failure of concrete structures in fire may have different reasons, e.g.; failure of the concrete, steel or bond. The failure of the concrete can be caused by the reduction of its strength or often more drastically by destructive spalling.

The high temperature properties have up to now usually been determined with normal strength (OS-) concretes. Extending the known data by linear extrapolation to cover also HS-concretes is not necessarily relevant, because due to their special composition and microstructure they may show high temperature phenomena up to now not perceived with OS-concretes. In recent years fire properties of different types of concrete (OS-concretes (K20 and K50), HS-concretes (K100) and ultra high strength concretes (K200 even K250)) have been investigated in Fire Technology

Laboratory of the Technical Research Center of Finland in cooperation with Technical University of Braunschweig.

The studies have comprised investigations of deformation behaviour, the loss of strength and the tendency to spalling in dependence of the composition and microstructure. Special attention has been paid to the chemical and physical background of the observed behaviour. The thermal stability and alterations of the microstructure have been investigated with the aid of DTA, dilatometry, Hg-porosimetry and SEM. Additionally, preliminary small scale tests concerning the spalling behaviour have also been performed.

2. HIGH STRENGTH CONCRETES

2.1 Materials

High temperature behaviour of three different HS-concretes were investigated experimentally /1/. The binders of the concretes were low heat Portland cement with 9 % (of the binder content) silica fume in concrete Si; rapid hardening Portland cement with 25 % class F fly ash in concrete Lt and blast furnace slag cement in concrete Tr. The mix proportions and some concrete data are given in Table 1, which also gives the respective data for a Finnish OS-concrete (OPC) /4/. The aggregate in the HS-concretes was granite-based sand and crushed diabase and in the OPC concrete mainly greywacke, sandstone, quartz and quartzite as coarse aggregates. The preparation and conditioning of the specimens are reported in /6, 7/.

Table 1. Mix proportions and concrete data.

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, kg/m^3	137	154	145	188
Superplasticizer	Scancem SP 62	Scancem SP 62	Conflow 200	-
- 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	0.265	0.45
Density, kg/m^3				
- 28 d	2648	2594	2654	2390
- > 90 d	2607	2537	2610	2390
Cube strength, MPa				
- 28 d	100.0	85.1	111.1	48.0
- > 90 d	132.3	115.7	124.9	36.0
Cylinder strength, MPa				
- > 90 d	106.0	90.7	84.6	32.9

2.2 Thermal stability

2.2.1 Deterioration reactions

When concrete is subjected to heat, different kind of transformations and reactions occur. Besides the crystal transformations and/or decarbonation occurring mainly in the aggregates degradation reactions cause a progressive breakdown of cement gel structure /8/. These were studied by the aid of differential thermal analyses (DTA) /1/. The various high strength binders as well as concretes show in the thermograms generally the same peak locations and peak heights as OS-concretes. Thus the same deterioration reactions occur in HS- and OS-concretes.

2.2.2 Thermal expansion of cement pastes and concretes

At high temperatures the thermal expansion of the concrete components determines the deformation behaviour and the strength of the composite material. Like almost all solids, the aggregates expand with increasing temperatures while the cement paste shrinks after exceeding a certain temperature level /4, 8/. So, the thermal incompatibilities of the aggregates and the cement paste matrix cause degradation of concrete.

When heated all the investigated cement pastes expand at first. The expansion of Si-, Lt- and Tr-pastes is higher than that of OPC-paste. At about 150 °C the cement pastes begin to shrink due to dewatering. With increasing temperatures, specimens shrink monotoneously up to about 570 °C. Then Si- and Lt-pastes nearly keep their length up to 800 °C, above which they again shrink strongly. Tr-and OPC-pastes shrink continuously up to 900 °C. OPC-paste shows the strongest shrinkage in the whole temperature region.

The thermal expansion of concrete is mainly determined by the aggregates. Thus, although the different high strength pastes showed markedly different expansion, the expansion of Si-, Lt- and Tr-concretes were very similar. The thermal expansion of the HS-concretes is in the whole temperature region clearly lower than that of OPC-concrete due to the higher binder content and the lower thermal expansion of the coarse aggregate used in them.

2.2.3 Alterations of the microstructure caused by thermal exposure

The microstructure of the concrete and its alterations were studied by means of mercury porosimetry measurements performed by the aid of a commercial high pressure porosimeter (pressure range from 1 bar to 2000 bar), so pores with radii of 4 nm -7.5 μm could be detected .

The measurements give directly the cumulative distribution of the pore volume versus pressure (respectively pore radius). Here, the results are presented as differential pore size distributions visualizing directly the abundance of different pore sizes or crack widths.

The specimens were small cores 8 mm in diameter and 40 mm in length, drilled out of concrete cylinders. The cores were heated with a heating rate of about 10 K/min up to the desired temperatures, which were kept constant for one hour. The cores were slowly cooled down to ambient temperature and stored under vacuum (10^{-2} mbar) in an desiccator until testing.

Figs. 1 and 2 show the pore size distributions of Si- and Tr-concretes. The first area beneath the distribution curves represents the capillary porosity and the second dotted area the porosity of the interfacial zone between the cement paste matrix and the aggregates as well as voids due to incomplete compaction and cracks caused by shrinkage of the paste /9/.

When considering the capillary porosity of the studied HS-concretes it ban be seen that their pore volume and mean pore radius are significantly smaller than in OPC-concrete /4/. At 20 °C like in all the temperature regions the pore volume and the mean pore radius of cement paste in Tr-concrete are distinctly smaller than those in Si- and Lt-concretes, the pore volume being biggest in Lt-concrete.

The temperature increase up to 105 °C causes in Si- and Lt-concretes an increase of the pore volume and the mean pore radius, whereas in Tr-concrete practically no change can be seen. The further increasing of temperature up to 450 °C leads in all three to a distinct increase of the porosity belonging to cracks in the interfacial zone and matrix.

The microstructure of the concrete determines the permeability of the concrete, which on the other hand controls the water expulsion from the concrete at normal as well as at elevated temperatures. Therefore the pore structure has a big influence on the spalling behaviour of the concrete at high temperatures. Because of their dense microstructure (small capillary porosity) - small permeability /2, 5/ - the HS-concretes may be more inclined to spall at fire temperatures than conventional concretes.

The water expulsion from the concretes (drying) was studied by measuring the weight loss of cylinders (diameter = 80 mm, length = 300 mm) at 105 °C (110 °C with Tr-concrete). Drying of Si-concrete was the slowest. Tr-concrete dried most rapidly and reached its final weight already in 20 days whereas Si- and Lt-concretes showed weight loss still after 100 days. Tr-concrete was dried at 110 °C, which of course accelerated the water expulsion somewhat. Because of lower drying Si-concrete may be suspected to have a higher risk of spalling than the others.

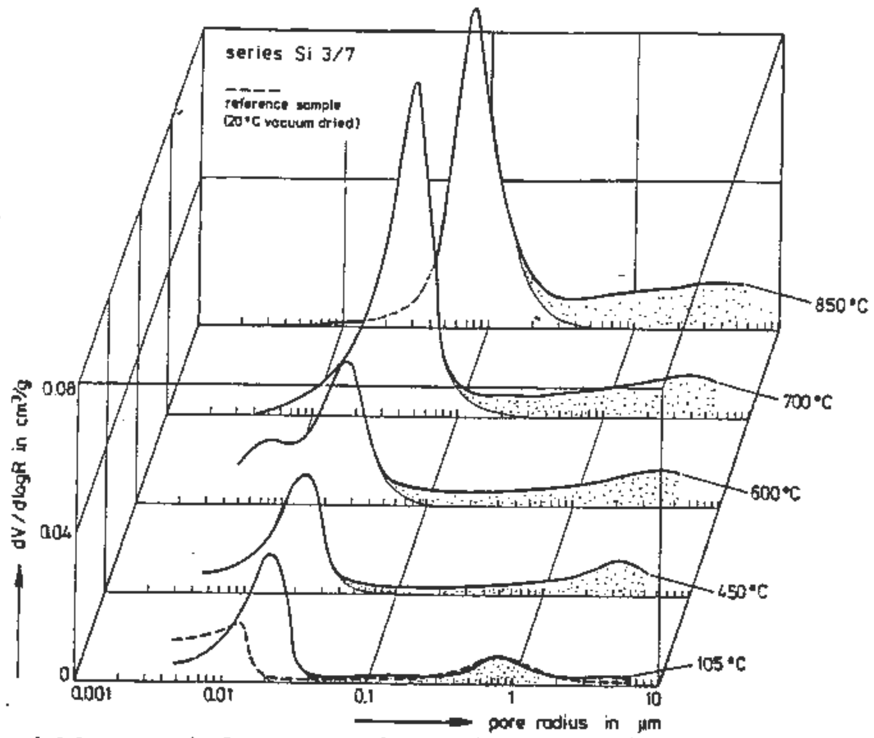

Fig. 1. Differential pore size distribution of heated Si-concrete.

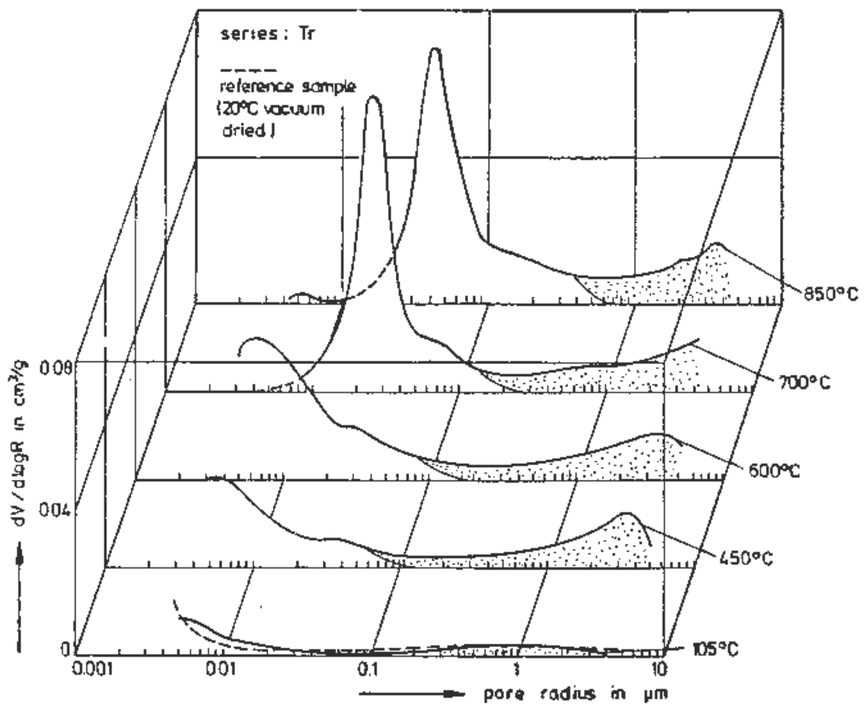

Fig. 2. Differential pore size distribution of heated Tr-concrete.

2.3 Mechanical behaviour

2.3.1 Test methods

Material properties obtained experimentally are closely related to the test method employed. In fire materials are subjected to transient conditions and so the properties should be determined under transient temperature conditions. The mechanical properties of the concrete at high temperatures were studied with steady state and transient tests:

- σ-ϵ-curves were determined with steady state tests using a constant strain rate of 0.5 % /min. From these results the compressive strength and the modulus of elasticity were also determined.
- Measurements of total deformation were carried out applying different constant loads during heating. The load levels were 0...70 % of the ultimate compressive strength at 20 °C.
- The modulus of elasticity at transient temperatures was determined with tests, in which the specimen was subjected to continuous cyclic loading during heating. The load varied between 2 and 20 % or 10 and 30 % of σ_{ult}(20 °C).
- For restraining tests the specimen was loaded and the measured strain was kept constant during heating. The influence of initial load level (15, 30 and 45 %) was studied.

In these tests a constant heating rate of 2 K/min was applied.

2.3.2 Test results

In the σ-ϵ-tests at steady state thermal conditions similar σ-ϵ-relationships were obtained for all three HS-concretes, Fig. 3 shows the σ-ϵ-curves of Lt-concrete. They differ distinctly from those of OPC-concrete (Fig. 4). The failure of HS-concrete is more brittle than that of OS-concrete. HS-concretes show already at 150 °C a loss of strength of about 30 %, whereas OPC-concrete up to a temperature of 350 °C indicates even a slight increase of strength. Although the modulus of elasticity of OPC-concrete at 20 °C is much lower than that of HS-concretes, its relative decrease is stronger in the whole temperature range (Fig. 5).

The total deformations of the investigated HS-concretes differ only slightly from each other. Fig. 6 shows the total deformation of Si- and OPC-concretes measured during heating. The smaller binder content and the higher thermal expansion of the coarse aggregates of OPC-concrete results in distinctly higher thermal expansion and lower transient creep than those in HS-concretes. When 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 a load level of 60 % of σ_{ult}(20 °C) heated specimens of Si- and Lt-concretes failed already soon after exceeding 100 °C, Tr-concrete specimens maintained their load bearing capacity with a load level of 70 % up to 110 °C and the OPC concrete specimens with a load level of 60 % even up to 450 °C.

Besides, at constant temperatures, the modulus of elasticity was determined also with transient tests corresponding better to the fire conditions. In these tests, during heating the specimen was subjected to continuous cyclic loading (1 cycle/min) varied from 2 to 20 % or from 10 to 30 % of the σ_{ult}(20 °C). The difference of the measured total deformations under different load levels

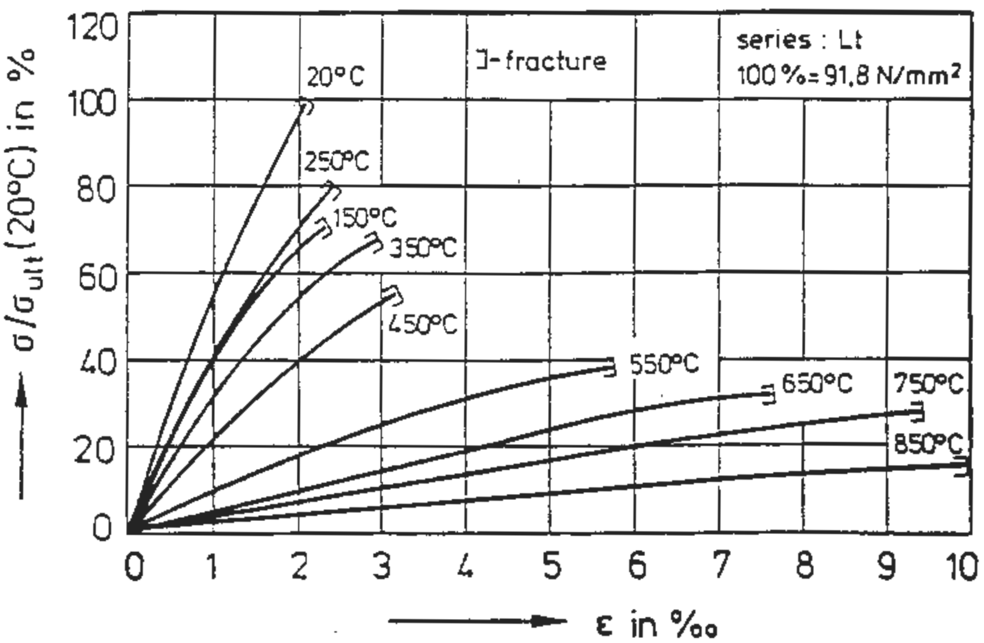

Fig. 3. Stress-strain relationships of Lt-concrete tested at high temperatures.

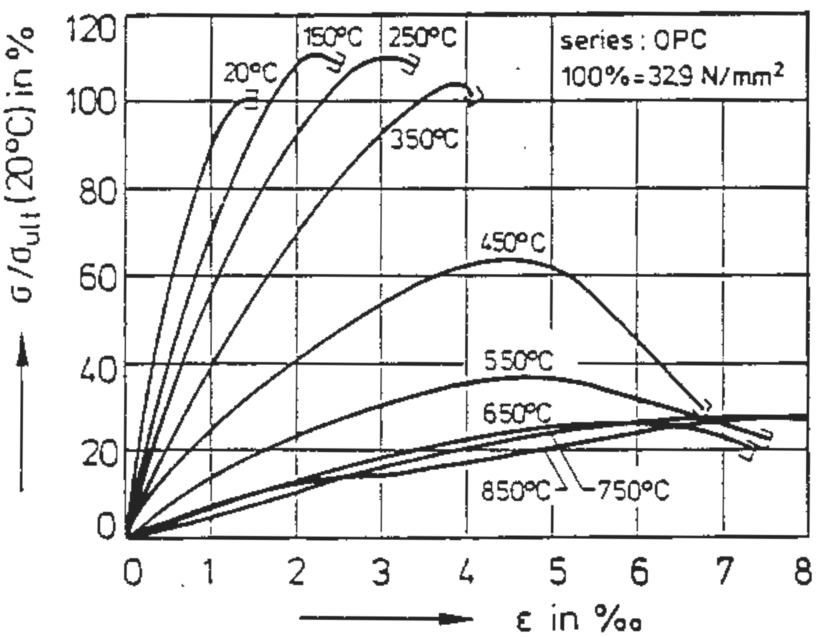

Fig. 4. Stress-strain relationships of OPC-concrete tested at high temperatures.

is considered the elastic deformation due to the corresponding stress difference.

Fig. 7 shows the modulus of elasticity of Lt-concrete determined with different tests, steady state as well as transient tests. It can be seen that values determined in transient tests decrease slower than in steady state tests. The decrease is smaller with higher load level (α = 10...30 %) than with lower

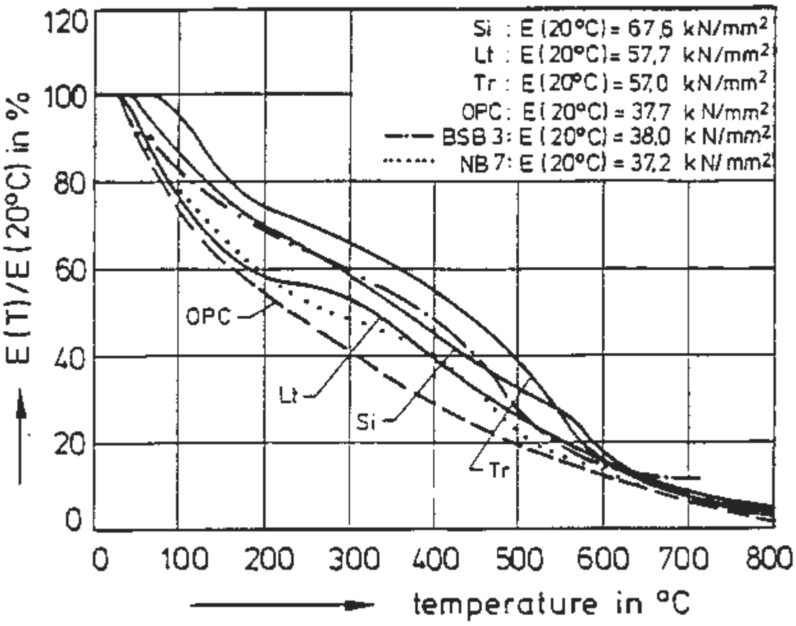

Fig.5. Modulus of elasticity of various high strength and normal strength concretes.

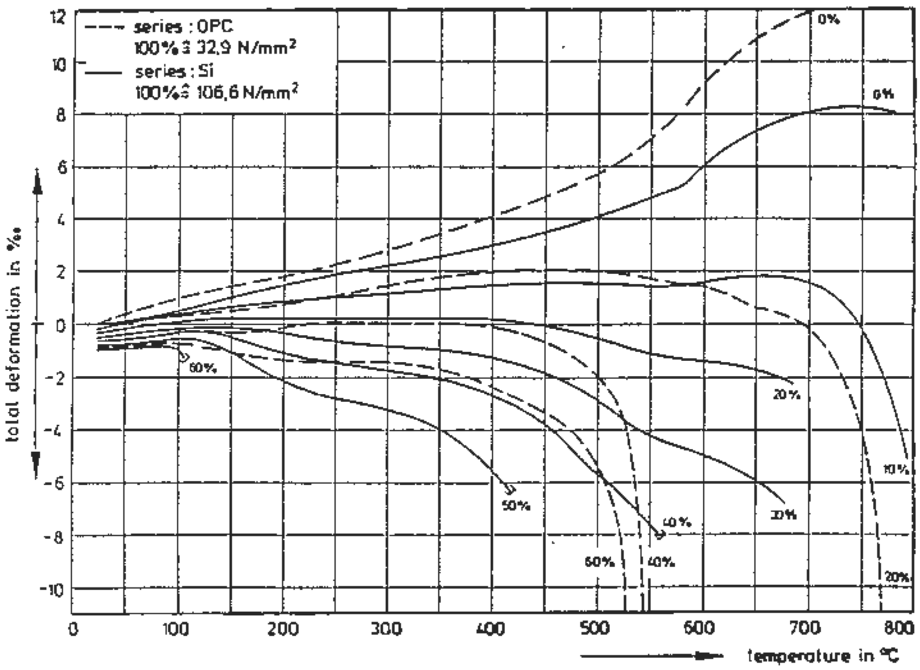

Fig. 6. Total deformation of loaded Si-concrete and normal strength OPC-concrete during heating.

(α = 2...20 %). The modulus of elasticity decreases most quickly in Lt-concrete and slowest in Tr-concrete up to about 500 C. Though the modulus of elasticity is an important characteristic especially in calculating the thermal behaviour of structures, the elastic strain contributes only a little to the load induced deformations. The transient component is predominent at temperatures over 100 ° C and the magnitude of the increase of elastic

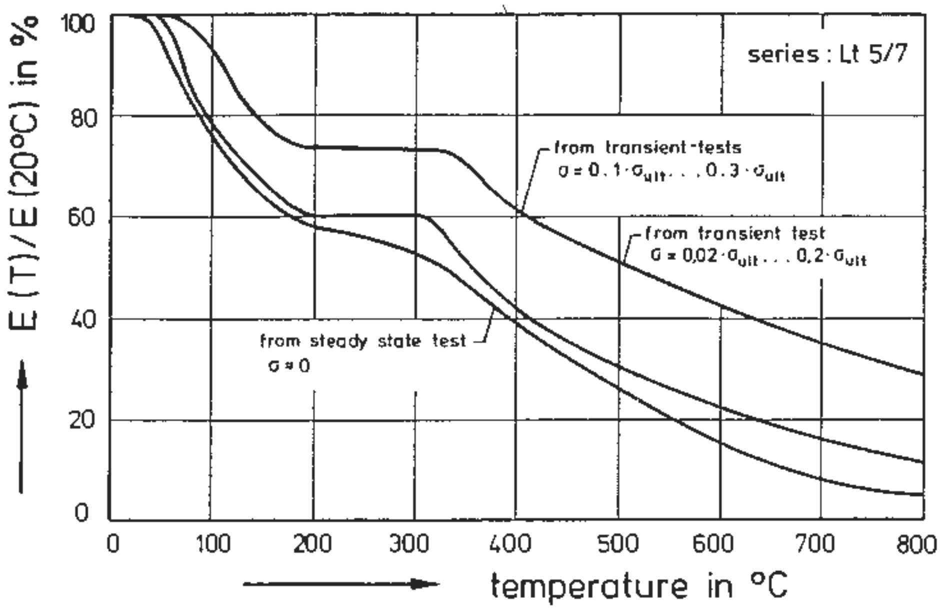

Fig. 7. Modulus of elasticity of Lt-concrete.

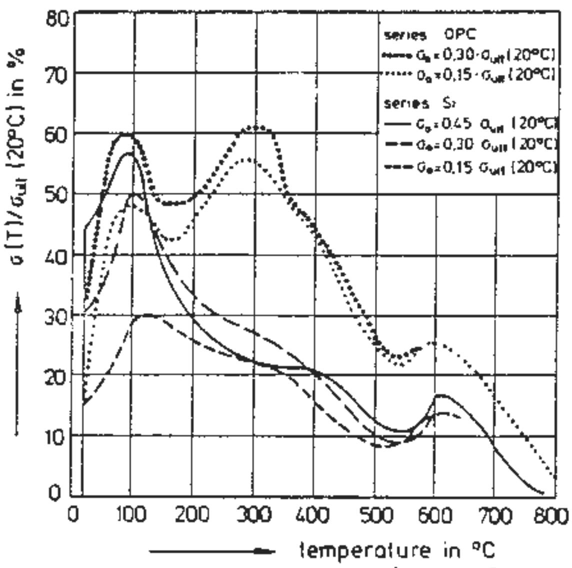

Fig. 8. Restraint forces of Si- and OPC-concretes.

strain component is at 150 °C only 1/4 - 1/8 and at 700 °C respectively only 1/5 - 1/25 of the transient strain /26/.

The development of restraint forces is determined by the temperature dependance of the modulus of elasticity, thermal expansion and creep. Because of their similarity in Si-, Lt- and Tr-concretes also the 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 at that temperature region. As expected, the OPC concrete shows higher relative restraint forces than the HS-concretes (Fig. 9).

Destructive spalling occurred in no specimen heated with a heating rate of 2 K/min. Some cylindrical specimens under load were heated with a maximum heating rate (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 100 x 100 x 400 mm^3) heated under load with the maximum heating rate spalling occurred in all HS-concretes causing failure of the specimen in Si- and Lt-concretes.

3. ULTRA HIGH STRENGTH CONCRETES

3.1 Materials

A research project for developing and investigating ultra high strength concretes (compressive strength > 200 MPa) is going on in Technical Research Centre of Finland. Up to now preliminary investigations have been performed on the high temperature behaviour of three types of these concretes.

Two of the investigated ultra high strength concretes, EL1 and EL2, had the same basic mix proportion and the aggregate was fine quartz. In EL2-concrete steel fibres (EE-fibres 18x0,6x0,3 mm) were used to improve the tensile strength and ductility of the otherwise brittle concrete. In concrete B6 the aggregate was bauxite. Table 2 gives the mix-proportions and some concrete data of these concretes.

Specimens were prisms (40x40x160 mm^3). After demolding the EL1 and EL2 specimens at the age of 1 day they were heat treated 6 days at 60 °C and then two days at 200 °C. This causes hydrothermal reactions between quartz and $Ca(OH)_2$ resulting in a very strong chemical bond in the interface between the cement paste matrix and the aggregates.

Table 2. Mix proportion and concrete data of ultra high strength concretes.

Concrete type	EL1	EL2	B6
Cement (PZ 55), % of dry-batch weight	27,8	27,8	23,1
Silica, % of dry-batch weight	8	8	6
Aggregate, % of dry-batch[3] weight			
- Quartz, 0 - 0,3 mm	64,2	64,2	
- Bauxite, 0 - 0,2 mm			16,6
0 - 3 mm			54,3
Mighty (42 % solution), % of binder content	6	6	6
Water/binder	0,35	0,35	0,253
Steel fibres (EE), % of dry-batch weight		13	
Compressive strength, MPa	190	242	192
Density, kg/m^3	2082	2316	2757

3.2 Test results

Preliminary experiments have been carried out with ultra high strength concretes to study their tendency to spalling /3/ and to find concrete mixes which could be used in fire conditions.

An EL1-concrete prism was heated in standard fire conditions. It exploded after 7 min into two pieces and the exploding continued so that 8,5 min after the start of the test the specimen was not to be seen any more. After the 39 min long test some fragments 5 - 10 mm in size were found in the furnace.

The thermal stability of EL1 concrete was also studied by the aid of DTA, Hg-porosimetry and by heating the specimen with constant heating rate of about 20 K/min following the behaviour of the material by the aid of acoustic emission analysis. The moisture content of the concrete was 2,3 - 3,0 %. At a temperature (surface temperature) of 280 °C the acoustic activities (caused by cracking) accelerated and at 310 °C the specimen exploded suddenly. The pressure of the pore water was then about 100 bar.

Steel-fibre concrete EL2 was studied by the aid of acoustic emission analysis, too. Various heating rates were applied (0,2 - 27 K/min).

- With a heating rate > 1K/min specimens broke suddenly, at a temperature of 300 -350 °C.
- With a heating rate of 0,5 K/min, at about 320 °C a 0,25 mm wide crack formed through the whole specimen.
- With a heating rate of 0,2 K/min several cracks of 0,05 mm in width (measured after cooling) formed in the specimens.

When heating a bauxite concrete (B6) specimen with a heating rate of 5 K/min, it exploded drastically at 300 °C. In standard fire conditions the specimen exploded 6 min after the start of the test. Moisture content of these specimens was 4 %. Specimens dried at 105 °C sustained the heating with a heating rate of 5 K/min up to 660 °C and in standard fire. The acoustic emission analysis showd that with heating rate of 5 K/min the destruction of the material began when the surface temperature was 270 °C.

The test have shown that the concretes EL1 and EL2 can not be used at high temperatures (even reasonably protected) due to their strong tendency to spalling even with very low heating rates. Bauxite concrete will be further investigated to find a realistic moisture content at which it could be used at fire conditions. If this succeeds with small unloaded specimens the influence of the loading will be studied using bigger specimens.

4 CONCLUSIONS

The fire behaviour of the concrete is strongly dependent of its microstructure and the binder content. The investigated high strength concretes showed, especially in the temperature reagion from 100 °C to 350 °C, 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

HS-concrete is more decisive than on that of OS-concrete because the cement paste matrix of HS-concrete must carry higher loads than in OS-concrete.

The cement paste of high and ultra high strength concrete is essentially denser than that of normal strength concrete and 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 them. Especially in ultra high strength concretes the very dense microstructure causes high risk of spalling.

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