

# HIGH TEMPERATURE BEHAVIOUR OF SELF-COMPACTING CONCRETE WITH LIMESTONE POWDER

Klaus Pistol\*, Frank Weise and Birgit Meng

BAM Federal Institute for Materials Research and Testing, BERLIN, GERMANY.

\*: corresponding author. [klaus.pistol@bam.de](mailto:klaus.pistol@bam.de)

## ABSTRACT

*Although concrete in general is a non-combustible material, the fire resistance of concrete structures depends, to a large extent, on the mechanical material behaviour. Fire tests have shown that SCC is often susceptible to explosive spalling due to fire exposure, in a similar manner to HPC. But there are hardly any studies available that report properties of specimens at high temperatures. Therefore, the authors have studied the mechanical behaviour of SCC to provide thermo mechanical characteristics for structural fire design. The analysed SCC reveals a significant differing thermal induced strength evolution in comparison to ordinary concrete.*

**Keywords:** fire resistance; stress-strain-relation, compressive strength; polypropylene fibres

## INTRODUCTION

Self-compacting concrete (SCC) is a high performance building material, whose fresh and hardened concrete properties have been tested intensively in the last two decades. However, the fire behaviour of SCC has not yet been sufficiently investigated. Although concrete in general is a non-combustible material, the fire resistance of concrete structures depends, to a large extent, on the material behaviour and additionally on the structural and geometrical parameters of the structural elements [0]. The material behaviour of ordinary concrete (OC) during a fire exposure was intensively analysed in the last century and the findings from that time are integrated in the European standard for the structural design of reinforced concrete structures EN 1992 (EC 2). The structural fire design is regularised in part 1-2 of EC 2 [0]. As a result of the implementation of EC 2, the fire resistance of concrete members and/or concrete structures can be verified with simplified calculation methods and/or advanced calculation models in addition to the common fire design procedure with tabulated data. For these calculation methods, thermo-mechanical material properties are required. In EC 2, different material specifications are made for ordinary concrete, high performance concrete (HPC) and steel. Main parameters of the stress-strain relationships of concrete at elevated temperatures ( $\theta$ ) are the compressive strength ( $f_{c,\theta}$ ) and the ultimate strain ( $\epsilon_{c1,\theta}$ ) corresponding to  $f_{c,\theta}$ . Values for these parameters are specified within a table for OC separately for quartzitic and calcitic aggregates as a function of temperature, whereby the compressive strength is related to the characteristic compressive strength at 28 days ( $f_{ck}$ ). For HPC, only values for the relative compressive strength ( $f_{c,\theta}/f_{ck}$ ) are given in EC 2, but no values for the ultimate strain. The comparison of the  $f_{c,\theta}/f_{ck}$  - values shows that OC as well as HPC lose their strength continuously with increasing temperature, whereby the strength of HPC decreases significantly in the lower temperature range. The difference in the thermal material behaviour of OC and HPC leads to different fire resistances of structures. This raises the question: What are the thermo-mechanical properties of SCC? In EC 2, no information regarding SCC is given. But structural engineers need valid data concerning the thermo-mechanical material behaviour of SCC for a reliable fire design of structures, all the more so as the composition and the microstructure of SCC is clearly different from OC and HPC.

Fire tests have shown that SCC is often susceptible to explosive spalling due to fire exposure, in a similar manner to HPC [0-0]. This leads to a reduction of the cross section of concrete members and to the loss of the thermal insulation of the reinforcing steel bars. As a consequence, the load-bearing capacity of reinforced concrete members is suddenly reduced. Currently, the most effective and economical method to prevent explosive concrete spalling is the application of polypropylene fibres (PP-fibres). Due to the thermal decomposition of the PP-fibres micro channels are created and simultaneously connected due to a net-like micro crack formation. This increases the permeability of fire exposed concrete and leads to a thermo-mechanical (micro crack formation) and a thermo-hydraulic (water vapour flow) stress

relief [0]. However, the stiffening effect of PP-fibres on the consistency of the fresh concrete has to be taken into consideration in developing SCC-mixtures with PP-fibres. Publications also exist that deal with the thermal induced change of mechanical properties of SCC [0-0].

There are hardly any studies available that report properties of specimens at high temperatures (steady-state tests) or during heating (transient tests). Most articles deal with the compressive strength of SCC-specimens after a heat treatment at the cooled-down stage (residual compressive strength). But this kind of measurement values is not entirely suitable for the evaluation of the fire resistance according to EC 2. In fact, for structural fire design thermo-mechanical properties of concrete need to be generated by tests recommended by RILEM [0-0]. Recently, a study on the thermo-mechanical behaviour of SCC at high temperatures was published by BAMONTE & GAMBAROVA [0]. However, they did not specifically consider transient creep tests, which are needed for comparing deformation properties of SCC at high temperatures with values given in EC 2. The aim of the present study is to provide usable data for structural fire design and to acquire new forms of knowledge on the specific material behaviour of SCC in the event of fire.

## EXPERIMENTAL SETUP

For this purpose, a powder-type SCC with a high amount of limestone powder was selected to represent an extreme example, as the main difference between SCC and OC/HPC is seen in the high amount of inert mineral powder. Limestone powder is often used to produce SCC because of its cost-effectiveness. The mix proportions and the fresh and hardened concrete properties of the SCC are indicated in *Table 7*.

*Table 7. Components and properties of the analysed SCC without PP-fibres (SCC-0PPf) and with 1.5 kg/m<sup>3</sup> PP-fibres (SCC-1.5PPf)*

SCC mix proportions [kg/m <sup>3</sup> ]		SCC-0PPf	SCC-1.5PPf
Cement CEM I 42,5 R		287	287
Limestone powder		287	287
Water		174	174
Aggregates (siliceous)	0-0.5 mm	310	310
	0.5-1.0 mm	191	191
	1.0-2.0 mm	175	175
	2.0-4.0 mm	119	119
	4.0-8.0 mm	119	119
	8.0-16.0 mm	673	673
Polypropylene fibres		-	1.5
Superplasticizer		3.5	9.3

Fresh concrete properties	SCC-0PPf	SCC-1.5PPf
Air void contents [%]	1.0	1.5
Slump flow [mm]	700	690
V-funnel flow time [s]	7.5	10.0

Hardened concrete properties	SCC-0PPf	SCC-1.5PPf
$f_{c,cube}^1$ [N/mm <sup>2</sup> ]	58	56
$f_{c,cube,90d}^1$ [N/mm <sup>2</sup> ]	62	60
$f_{c,cyl}^2$ [N/mm <sup>2</sup> ]	50	48
$f_{c,cyl,90d}^2$ [N/mm <sup>2</sup> ]	58	53
Density [g/cm <sup>3</sup> ]	2.3	2.3

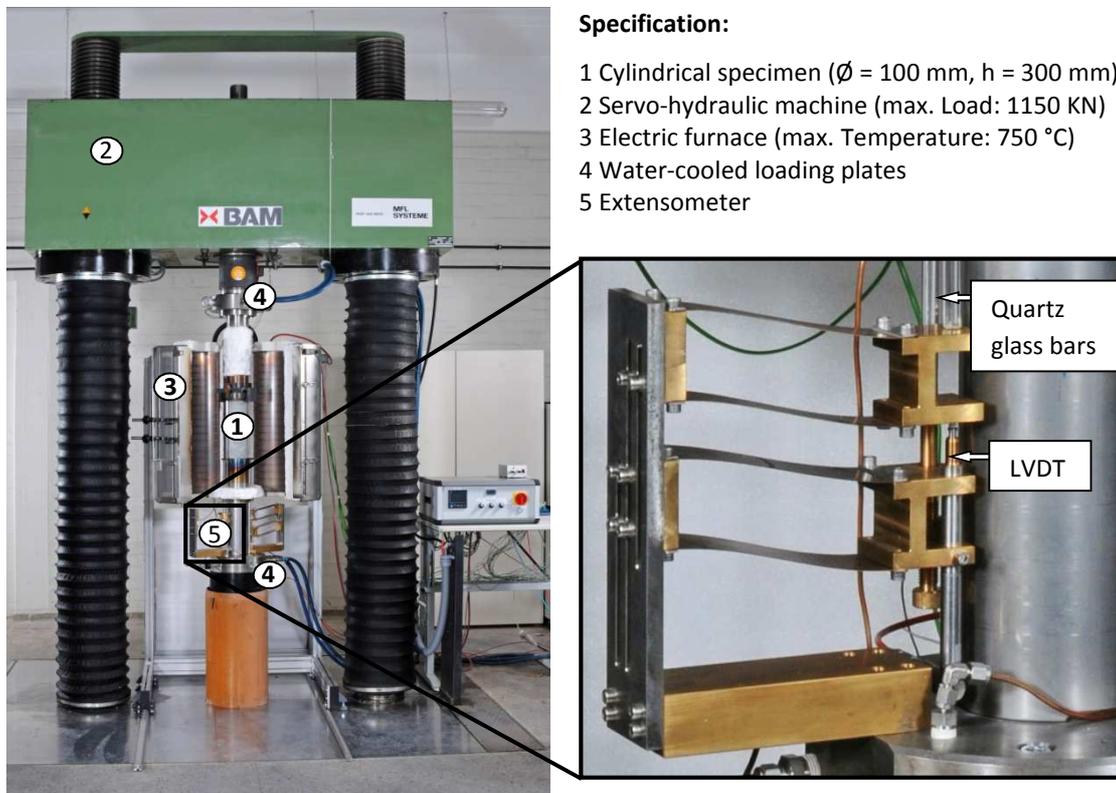
<sup>1</sup>Measured at cubic specimens with 150 mm side length.

<sup>2</sup>Measured at cylindrical specimens with 100 mm diameter and 300 mm height.

Specimens with  $1.5 \text{ kg/m}^3$  (SCC-1.5PPf) and without PP-fibres (SCC-0PPf) were produced to investigate systematically the influence of PP-fibres on the thermo-mechanical behaviour.

Temperature ( $\theta$ ), stress ( $\sigma$ ) and strain ( $\epsilon$ ) are the main test parameters in thermo-mechanical tests, which can be constant or transient during testing. SCHNEIDER describes in [0] six practical testing regimes as a result of different combinations of these parameters. For the determination of concrete properties for structural fire design, two testing regimes are decisive: the steady-state compressive strength test [0, 0] and the transient creep test [0]. In the present study, specimens with a diameter of 100 mm and a height of 300 mm were tested in steady-state compressive strength tests. *Figure 12* shows the thermo-mechanical testing machine and its specification. The machine is equipped with a special extensometer which enables the measurement of sample deformations during the thermo-mechanical loading. Thin bars of quartz glass connect the loading plates to displacement transducers in order to measure the length change of the specimen. They are guided by a spring system that ensures the parallel movement of the quartz glass bars. Although in real fire scenarios concrete members are exposed to fast increasing temperatures, the compressive strength as a material property has to be measured at constant temperatures in steady-state tests. This ensures that the tested specimens have hardly any temperature gradient between the heated surface and the core, which prevents additional internal stresses.

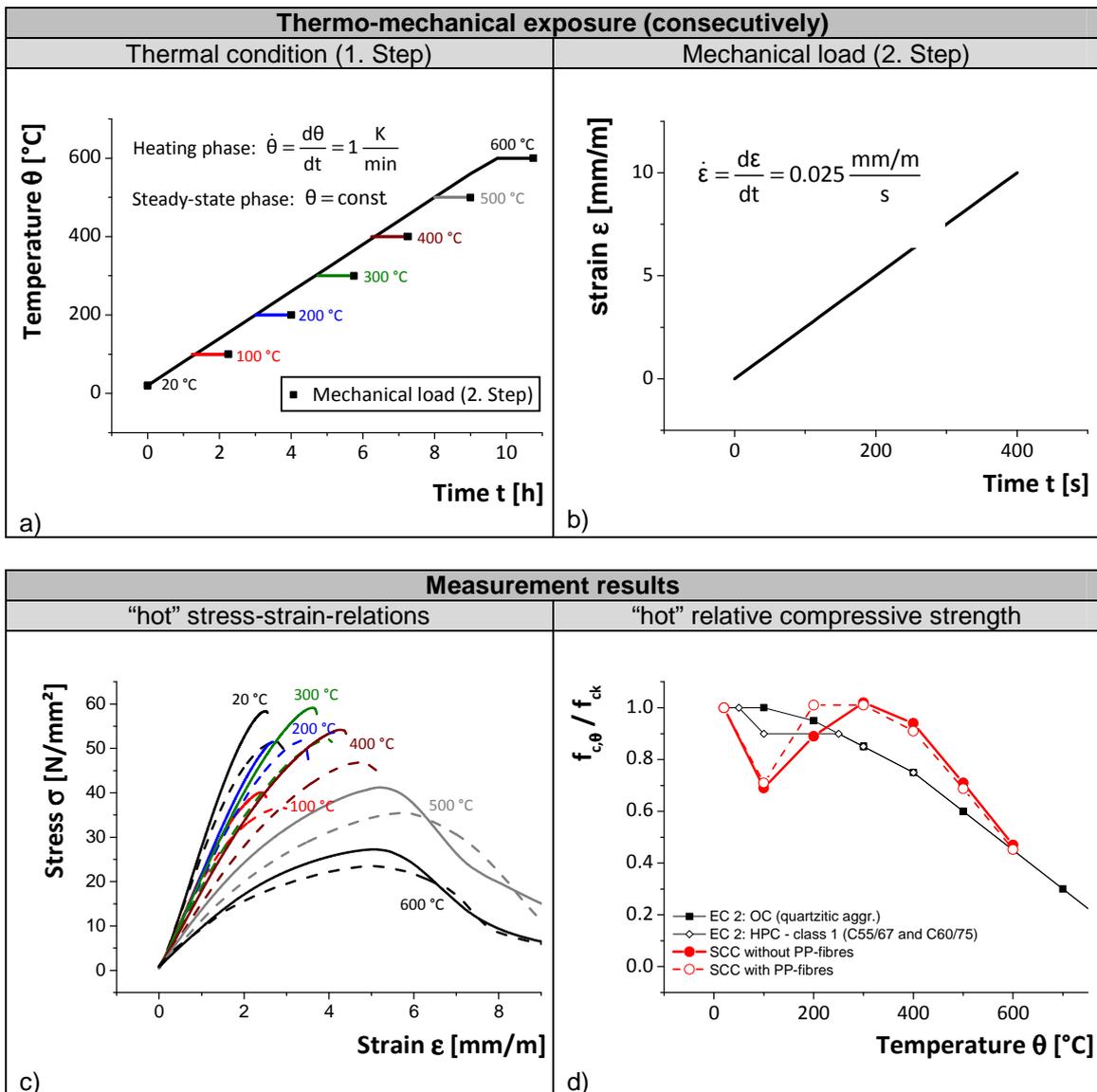
*Figure 12. Thermo-mechanical testing machine*



## RESULTS AND DISCUSSION

Table 8 indicates the thermo-mechanical exposure (top) and the results (bottom) of the analysed SCC. At first, specimens are heated very slowly (1 K/min) until reaching the target temperatures and then followed by a steady temperature phase for at least one hour in order to avoid a temperature gradient during heating (Cf. cell a) in Table 8)

Table 8. "Hot" compressive strength test according to the RILEM recommendation [0, 0]: Thermo-mechanical exposure (schematic) and results measured at SCC-OPPf (continuous line) and SCC-1.5PPf (dashed line)



Afterwards, the mechanical load is applied to the “hot” specimen with a constant loading rate (Cf. cell b) in *Table 8*). The thermo-mechanical test device of BAM enables a strain-controlled loading (0.025 %/s), which allows for the determination of the post-failure softening behaviour. As a measurement result, the stress-strain-relations for different temperatures are depicted in the cell c) of *Table 8*. The diagram shows the evolution of the compressive strength and the uniaxial strain at different temperature levels. The dashed lines indicate the results of SCC with 1.5 kg/m<sup>3</sup> PP-fibres (SCC-1.5PPf). As expected, the curves reveal generally that, at higher temperatures, the strength decreases whereas the ductility increases. But it is interesting to note a major decline of compressive strength at 100 °C. Both SCC-0PPf and SCC-1.5PPf retain a significant strength reduction at that temperature of nearly 30 % in comparison to the initial compressive strength at 20 °C. However, this phenomenon is known from high temperature tests at HPCs (e.g. [0]). But the initial strength of the analysed SCC (Cf. *Table 7*) is at the border between OC and HPC, similar to most of the SCCs used in practise. For a better visualisation of this differing behaviour the relative compressive strength ( $f_{c,\theta}/f_{ck}$ ) is plotted against temperature in cell d) of *Table 8*. A comparison with values of OC and HPC from EC 2 show that it is not always useful to classify concrete into strength classes. Furthermore it is remarkable that at 300 °C the initial strength level is reached once again, followed by a monotonically decreasing strength development. At 200 °C, the influence of the PP-fibres is noticeable. Specimens with PP-fibres reach at 200 °C already their initial strength and specimens without PP-fibres, in contrast, reach only 90 % of their initial strength. The authors assume that this phenomenon may be explained by the activation of van der Waals’ forces due to a faster dehydration and densification of the cement/limestone-matrix in specimens with PP-fibres, but this will be the object of further investigations. Currently, the authors are monitoring the specific damage process by acoustic emission analyses during thermo-mechanical tests.

## CONCLUSIONS AND OUTLOOK

To summarise the findings of this contribution the following conclusions can be drawn:

- The properties of SCC at high temperatures have not been sufficiently investigated yet. Furthermore, the specific composition of SCC allows no clear classification according to EC 2.
- The analysed SCC reveals a significant differing thermal induced strength evolution in comparison to relevant values of OC and HPC in EC 2.
- This leads to two consequences: on the one hand, the analysed SCC has to be classified as a HPC-class 2 (C 70/85 and C 80/95) according to EC 2, and on the other hand, the values for the calculation of the fire resistance of members made of SCC still has to be experimentally determined.

Another important material behaviour, which needs to be determined for structural fire design is the deformation of concrete during heating under constant load (transient creep). Values for the temperature dependent ultimate strains ( $\epsilon_{c1,\theta}$ ) given in EC 2 can be derived from transient creep tests. This will be the subject of a further publication.

## LIST OF REFERENCES

- Kordina, K. & Meyer-Ottens, C., *Beton Brandschutz Handbuch*, Verlag Bau+Technik GmbH, Düsseldorf, 1999. (German)
- EN 1992-1-2, *Eurocode 2: Design of concrete structures – Part 1-2: General rules – Structural fire design*.
- Blontröck, H. & Taerwe, L., *Exploratory spalling tests on self compacting concrete*, Proceedings: 6<sup>th</sup> International Symposium on Utilization of High Strength / High Performance Concrete, Leipzig, 2002, pp. 659-666.
- Boström, L., *Self-compacting concrete exposed to fire*, Proceedings: Third International Symposium on Self-Compacting Concrete, Reykjavik, Island, 2003, pp. 863-869.
- Persson, B., *Fire resistance of self-compacting concrete, SCC*, Materials and Structures, Vol. 37, No. 9, 2004, pp. 575-584.
- Horvath, J., Hertel, C., Dehn, F. & Schneider, U., *Influence of storage conditions on the temperature behaviour of Self-Compacting Concrete*, Beton- und Stahlbetonbau, Vol. 99, No. 10, 2004, pp. 813-815.
- Reinhardt, H.W. & Stegmaier, M., *Self-Consolidating Concrete in Fire*, ACI materials journal, Vol. 103, No. 2, 2006, pp. 130-135.
- Ye, G., De Schutter, G. & Taerwe, L., *Spalling behaviour of small self-compacting concrete slabs under standard fire conditions*, Proceedings: 5<sup>th</sup> International RILEM Symposium on Self-Compacting Concrete, Ghent, Belgium, 2007, pp. 799-804.
- Pistol, K., Weise, F. & Meng, B., *Polypropylene fibres in high performance concretes – Mechanism of action in the event of fire*, Beton- und Stahlbetonbau, Vol. 107, No. 7, 2012, pp. 476-483.
- Noumowé, A., Carré, H., Daoud, A. & Toutanji, H., *High-strength self-compacting concrete exposed to fire test*, Journal of Materials in Civil Engineering, Vol. 18, No. 6, 2006, pp. 754-758.
- Sideris, K. K., *Mechanical characteristics of self-consolidating concretes exposed to elevated temperatures*, Journal of Materials in Civil Engineering, Vol. 19, No. 8, 2007, pp. 648-654.
- Pineaud, A., *Contribution à l'étude des caractéristiques mécaniques des Bétons Auto-Plaçants et application à l'industrie de la préfabrication*, PhD-Thesis, University of Cergy-Pontoise, France, 2007 (French)
- Annerel, E., Taerwe, L. & Vandeveld, P., *Assessment of temperature increase and residual strength of SCC after fire exposure*, Proceedings: 5<sup>th</sup> International RILEM Symposium on Self-Compacting Concrete, 2007, Ghent, Belgium, 2007, pp. 715-720.

- Anagnostopoulos, N., Sideris, K. K. & Georgiadis, A., *Mechanical characteristics of self-compacting concretes with different filler materials, exposed to elevated temperatures*, *Materials and Structures*, Vol. 42, No. 10, 2009, pp. 1393-1405.
- Robert, F. & Colina, H., *The influence of aggregates on the mechanical characteristics of concrete exposed to fire*, *Magazine of Concrete Research*, Vol. 61, No. 5, 2009, pp. 311-321.
- Fares, H, Noumowe, A. und Remond, S., *Self-consolidating concrete subjected to high temperature, Mechanical and physico-chemical properties*, *Cement and Concrete Research*, Vol. 39, No. 12, 2009, pp. 1230-1238.
- Annerel, E. & Taerwe, L., *Strain development of traditional and self-compacting concrete during fire*, *Proceedings: 6<sup>th</sup> International Conference „Structures in Fire“*, East Lansing, USA, 2010, pp. 751-759.
- Tao, J., Yuan, Y. & Taerwe, L., *Compressive strength of self-compacting concrete during high-temperature exposure*, *Journal of Materials in Civil Engineering*, Vol. 22, No. 10, 2010, pp. 1005-1012.
- Khaliq, W. & Kodur, V., *Thermal and mechanical properties of fiber reinforced high performance self-consolidating concrete at elevated temperatures*, *Cement and Concrete Research*, Vol. 41, No. 11, 2011, pp. 1112-1122.
- Bamonte, P. & Gambarova, P. G., *A study on the mechanical properties of self-compacting concrete at high temperature and after cooling*, *Materials and Structures*, Vol. 45, No. 9, 2012, pp. 1375-1387.
- Tao, J., Liu, X., Yuan, Y. & Taerwe, L., *Transient strain of self-compacting concrete loaded in compression heated to 700 °C*, *Materials and Structures*, Vol. 46, No. 1-2, 2013, pp. 191-201.
- RILEM TC 129-MHT, *Test methods for mechanical properties of concrete at high temperatures, Part 3: Compressive strength for service and accident conditions*, *Materials and Structures*, Vol. 28, No. 7, 1995, pp. 410-414.
- RILEM TC 200-HTC, *Mechanical concrete properties at high temperatures – modelling and applications, Part 2: Stress-strain relation*, *Materials and Structures*, Vol. 40, No. 9, 2007, pp. 855-864.
- RILEM TC 129-MHT, *Test methods for mechanical properties of concrete at high temperatures, Part 7: Transient creep for service and accident conditions*, *Materials and Structures*, Vol. 31, No. 5, 1998, pp. 290-295
- Schneider, U., *Concrete at high temperatures – a general review*, *Fire Safety Journal*, Vol. 13, No. 1, 1988, pp. 55-68.
- Huisman, S., Weise, F., Meng, B. & Schneider, U., *Transient strain of high strength concrete at elevated temperatures and the impact of polypropylene fibres*, *Materials and Structures*, Vol. 45, No. 5, 2012, pp. 793-801.
- Diederichs, U., Jumppanen, U.-M. & Penttala, V., *Behaviour of high strength concrete at high temperatures*, *Helsinki University of Technology, Department of Structural Engineering, Report 92*, Espoo 1989.