5th International RILEM Symposium on Self-Compacting Concrete
3-5 September 2007, Ghent, Belgium

ASSESSMENT OF TEMPERATURE INCREASE AND RESIDUAL STRENGTH OF SCC AFTER FIRE EXPOSURE

E. Annerel (1), **L. Taerwe** (1) **and P. Vandevelde** (2)

(1) Magnel Laboratory for Concrete Research, Ghent University, Belgium

(2) Fire Safety Laboratory, Ghent University, Belgium

Abstract

Generally concrete structures have a very good fire resistance. Although damage to the concrete gradually appears with increasing temperature, concrete structures in most cases don't collapse during a fire. It is of economical interest to reuse the structure after appropriate repair. Therefore it is necessary to determine the temperature to which the concrete structure has been exposed. Knowledge about the residual concrete properties after fire exposure is also needed. This paper deals with some fundamental aspects of a scientific and systematic methodology to assess the damage and to estimate the residual concrete strength.

1. INTRODUCTION

The effect of fire on the strength of traditional concrete has been studied for a long time and typical models can be found in codes (Eurocode 2, part EN 1992-1-2:2004). However, the behaviour of SCC under fire load is not yet widely investigated. One of the main topics in fire research today is the assessment of the residual strength after fire exposure. Concrete that is heated to high temperatures develops cracks and changes in colour from red (300-600°C) to whitish grey (600-900°C) and buff (900-1000°C). In [1] and [2] it is shown that both alterations can be linked to the residual strength since this is a function of the temperature. Storage of the concrete after fire exposure under water or in air also has an influence on the strength [3].

2. COMPRESSIVE STRENGTH REDUCTION

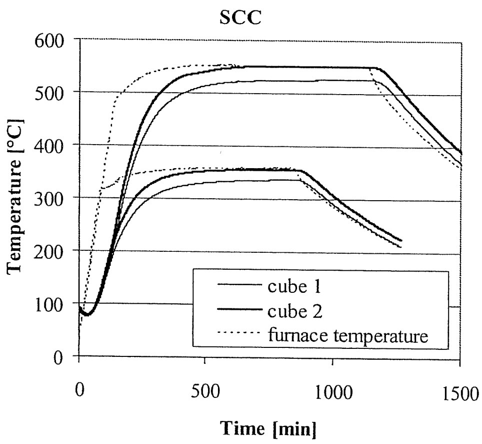
Table 1 gives the mix design of the self-compacting concrete (SCC) and the traditional concrete (TC) used in this test program. 150mm cubes were cured for 4 weeks in an air-conditioned room at a RH >90% and a temperature of 20±1°C, after which they were stored at 60% RH and 20±1°C for drying until the testing age of 17 weeks. During the three weeks before testing, the SCC cubes were dried at 105°C to avoid explosive spalling.

Two cubes were heated for each of the examined temperature levels (till 800°C). Figure 1 shows the increase of temperature in the centre of the cubes for heating to 350°C and 550°C. The drop at the start of the curves is caused by the initial temperature of the oven which is

20°C, while the SCC cubes were preheated to 105°C. The heating rate is 3.5°C/min and the target temperature is held for 750 minutes. The cubes were cooled in ambient air after removal from the oven. Figure 2 presents the mean residual compressive strength immediately after cooling. θ_0 is 20°C for TC and 105°C for SCC. Both curves are situated around the Eurocode curve for normal siliceous concrete [4].

Table 1: Concrete mix design

	SCC	TC
sand [kg/m³]	782	640
gravel 2-8 mm [kg/m³]	300	525
gravel 8-16 mm [kg/m³]	340	700
portland cement I 52.5 [kg/m³]	400	350
water [kg/m³]	192	165
limestone powder [kg/m³]	300	-
superplasticizer [l/m³]	2.90	-
W/C [-]	0.48	0.47
compressive strength 28d [N/mm²]	65.9	56.5



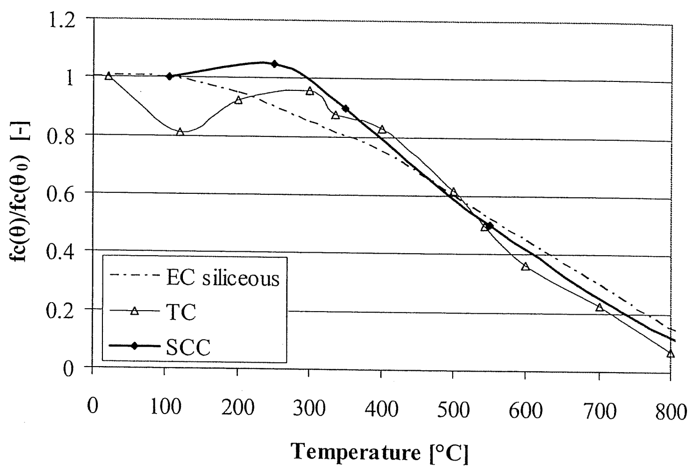


Figure 1: Time-temperature curves (left)
Figure 2: Residual compressive strength (right)

3. CHANGE IN COLOUR AND POROSITY

At an age of 2 months two cores were drilled out of one 150mm cube. The cores were sawn in 6 discs and polished. This was repeated for a cube made at a later time. In total 24 discs were obtained for each type of concrete. The samples were dried till testing time for at least two weeks at 60°C. Two discs (belonging to different mixtures in time) were heated without mechanical load at a heating rate of 30°C/min to the target temperature, which was held constant for 1h. The discs were slowly cooled down in the oven. The specimens were tested immediately after cooling or were stored at 60°C till testing.

The colour is measured with an X-rite SP60 spectrophotometer according to the CIE Lab-colour space. In this colour system 'L' is the lightness with values between 0 (black) and 100 (white). 'a' is spread between magenta (positive values) and green (negative values). 'b' is positioned between yellow (positive values) and blue (negative values). The aggregates were masked with black ink to minimize the effect of the colourful aggregates.

During heating the colour describes an elliptical path in the a*b*-colour space (Figure 3a). A peak is noticeable around 300°C corresponding to the development of a red tint (Figure 3b) and of a yellow tint (Figure 3c). The curves are similar for SCC and TC, except for the yellow tint at 800°C. The development of a buff tint can be seen in figure 3a for TC at temperatures of 1000°C and 1160°C.

The difference in the elliptical path between SCC and TC can be attributed to the combination of the change in concrete composition and the fixed aperture of 8mm of the spectrophotometer. Because SCC has less coarse aggregates but more cement matrix than TC, the colour will be measured over a smaller number of masked aggregates and a larger amount of cement matrix. This results in the observed difference, because the greater amount of the colourful sand particles in the cement matrix is not masked.

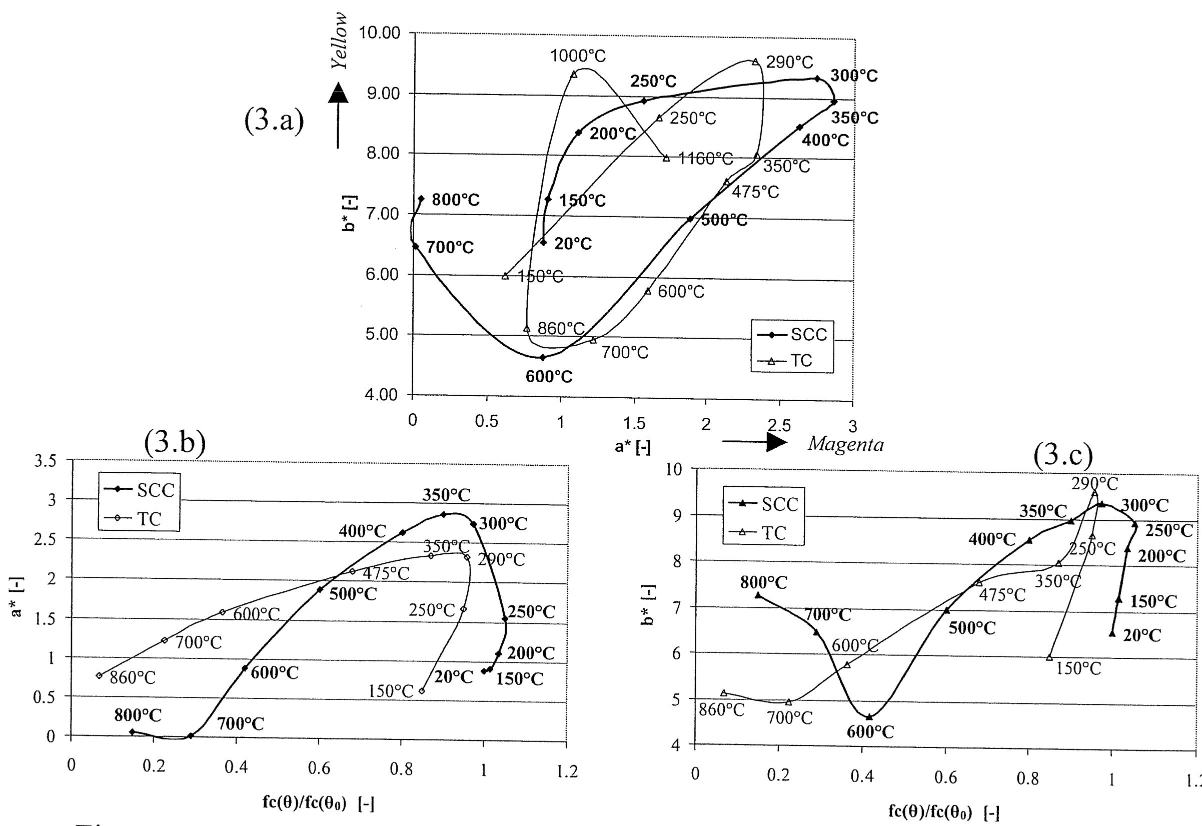


Figure 3: (L)ab- measurements and relation to the compressive strength reduction

For the microscopic determination of the porosity, the surfaces were completely blackened and the pores and cracks were filled with white powder ($BaSO_4$). A picture was obtained by a flatbed scanner and analysed with the standard image processing programme ImageTool. The total porosity, given as the ratio of the white area to the black area (cf. Figure 4a) and the size distribution for pore diameters larger than 50 micrometre (cf. Figure 7a) were determined. No spalling occurred due to the drying period of two weeks at 60°C.

Figure 4a presents the total porosity in relation to the heating temperature. A curve can be fitted to the measured points, which shows a constant value until a transition temperature from where it follows an almost linear increase. This type of curve is also found in [1] for Thames Valley aggregate concrete. SCC and TC have a different transition temperature, respectively 400°C and 250°C. This is because SCC has less coarse aggregates which results in a lower contact surface between the aggregates and the cement matrix (interfacial zone). Cracks in this zone caused by differences in thermal expansion are therefore also less pronounced. However, these interfacial cracks have an important contribution to the total porosity as will be explained further. The difference in interfacial crack width between SCC and TC is clearly visible on the polished specimens. The slope of the increasing part of the curves apparently depends on the testing conditions (size of samples, heating rate, heating duration, method of cooling) but is almost the same for the SCC and TC tested in this research project.

The same experimental data are plotted in Figure 4b, which gives a direct relation between the total porosity and the strength loss. Until the transition temperature no difference in porosity can be measured although there is a certain degree of strength degradation. Other methods as SEM and MIP do show a variation in porosity [5], because they analyse pores with a smaller diameter than 50 micrometre, which is the minimum class detected with the flatbed scanner. In [1] and [2] it is mentioned that the transition temperature can be easily determined from drilled cores and that this point can be considered as the onset of strength degradation. It would be useful if also the temperature above the transition temperature could be linked in absolute terms to a change in porosity. However, this is difficult, because not only the heating and cooling conditions have their influence on the porosity, but also the storage conditions after fire (see section 5 on recuring).

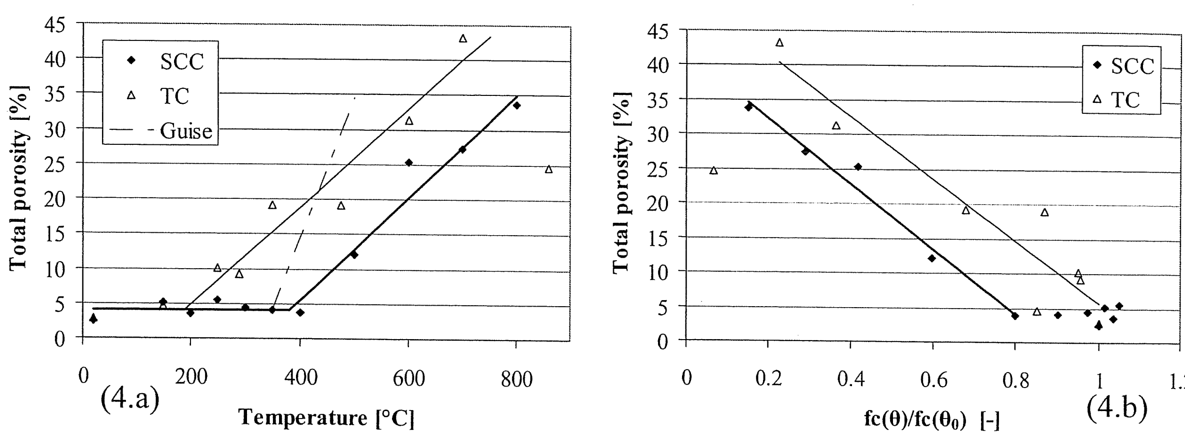


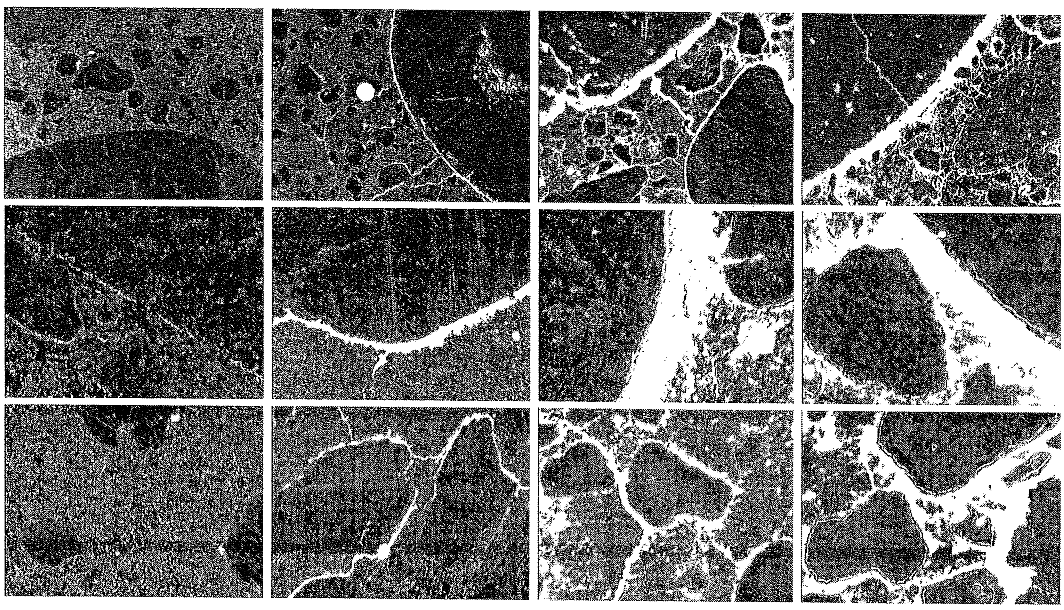
Figure 4: Relation temperature – total porosity – strength decrease

4. INTERFACIAL AND CEMENT MATRIX CRACKS

As can be seen in figure 5, cracks develop with increasing temperature. The main cause is the difference in thermal expansion between the aggregates and the cement matrix. Interfacial cracks develop around the coarse aggregates, while cement matrix cracks start around the sand particles and get connected at higher temperatures.

The crack width development is also measured and related to the residual strength (cf. Figure 6).

From figure 7a it can be seen that the increase in porosity is spread over all measuring classes. The peak around 1000 micrometre can be attributed to the interfacial cracks. From this size distribution the influence on porosity of the interfacial cracks and the cement matrix cracks can be determined (figure 7b). It appears that they increase both at the same rate.



35x

210x

210x

Figure 5: Crack development at 20°C (left), 400°C, 600°C, 800°C (right) in the interfacial zone (top: magnification x35; middle: x210) and the cement matrix (lower: x210).

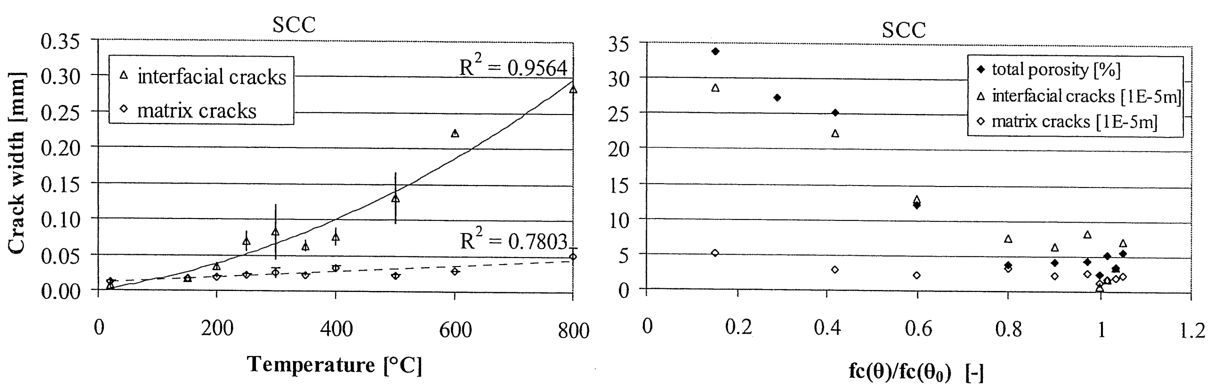


Figure 6: Relations between crack width, temperature and residual strength

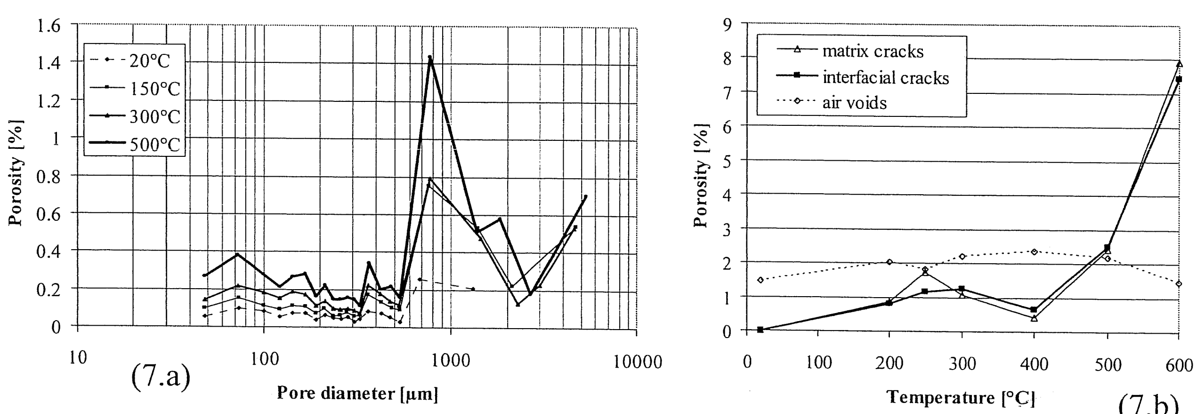
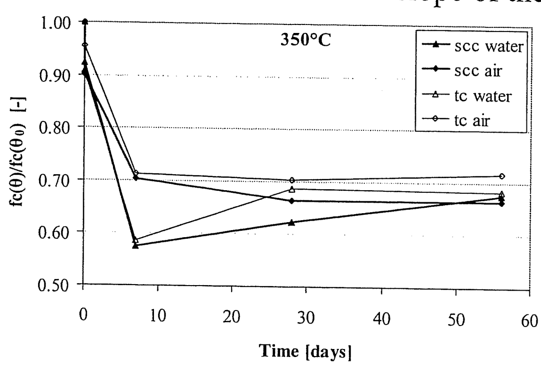


Figure 7: Size distribution (left) and the influence on porosity of the cracks (right)

5. RECURING

150mm cubes were heated at 350°C and 550°C, after which they were stored under water or in air for 7, 28 and 56days. The test parameters are the same as mentioned before. Figure 8 illustrates that the strength decreases to a minimum at 7days and that it recovers from then on. The strength recovery is faster for the storage under water. Except for 'TC 550°C water recured' the strength at 56 days is lower than the strength immediately after cooling. These results should be considered when evaluating the residual strength of a concrete member.

The change in porosity has also been studied under recuring conditions. The first results again show a good relation between the change in strength and porosity. However, the amount of porosity corresponding to a given strength reduction is not the same as in figure 4a, due to the differences in the testing parameters. Therefore the influence of the testing parameters should be studied to calibrate the slope of the curve.



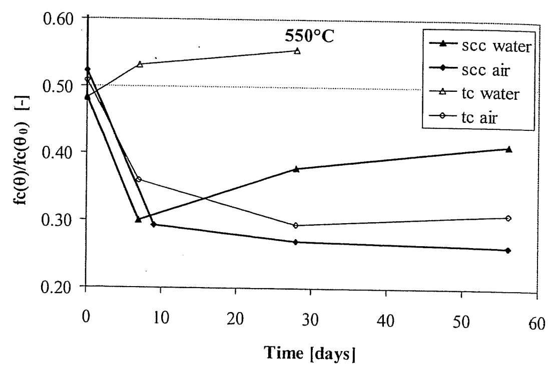


Figure 8: Strength recovery during recuring

6. CONCLUSIONS

- A transition temperature can be noticed in the porosity-temperature curve, which is higher for SCC than for TC.
- Interfacial and cement matrix cracks have a similar influence on the total porosity.
- After 56 days of recuring the strength is still lower than immediately after cooling.
- Measurements of colour changes and porosity have a good potential for assessing the residual strength of concrete after fire exposure. However, further research into the influence of testing parameters is necessary.

REFERENCES

[1] Guise, S.E., 'The Use of Colour Image Analysis for Assessment of Fire Damaged Concrete', PhD thesis (The University of Aston, 1997).

[2] Felicetti, R., 'Digital Camera Colorimetry for the Assessment of Fire-Damaged Concrete', in 'Fire Design of Concrete Structures: What now? What next?', Proceedings of the Workshop, Milan, December, 2004 (fib Task Group 4.3 'Fire Design of Concrete Strcutures') 211-220.

[3] Poon, C.S., 'Strength and Durability Recovery of Fire-Damaged Concrete after Post-Fire-Curing', *Cement and Concrete Research* **31** (2001) 1307-1318.

[4] EN 1992-1-2: 2004, 'Eurocode 2: Design of Concrete Structures – Part 1-2: General Rules – Structural Fire Design', CEN, Brussels

[5] Liu, X., 'Microstructural Investigation of Self-Compacting Concrete and High-Performance Concrete during Hydration and after Exposure to High Temperatures', PhD thesis (Ghent University, 2006).