Assessment of the Residual Strength of Concrete after Fire Exposure

Annerel, ir. Emmanuel ; Taerwe, Prof. Luc

ABSTRACT

Generally concrete structures have a very good fire resistance. After fire, it is of economical interest to reuse the structure after appropriate repair based on a reliable assessment of the residual strength. This paper deals with some fundamental aspects of a scientific and systematic methodology to assess the damage and to estimate the residual concrete strength based on the change in colour and porosity.

Tests show a clear relationship between the increase in temperature (up to 1160°C) and the number of cracks. The colour changes from red to whitish grey and buff. Estimation of the residual strength is possible, because of the known relationships between temperature and the concrete strength degradation. At first sight this method is promising, but the number of cracks and the change in colour are influenced by the test parameters. This alters the relationships and this should be considered when assessing the residual strength. Furthermore, these relationships change as the concrete ages.

The storage conditions after fire have an important influence on the residual strength. The variation of the compressive strength (till 56days) is determined for different temperatures and for storage in air and under water. A minimum around 7-28 days can be noticed.

The difference in strength degradation due to a rapid cooling under water, and an alteration of the rate of heating and the duration of the target temperature are examined. It seems that the cooling method is most critical.

The colour changes are measured for different time steps and temperatures up to 600°C. The Schmidt Rebound Hammer degradation is also examined in time for storage of these samples under water and in air.

The investigated concretes are self-compacting concrete and traditional (siliceous and calcareous) concrete.

KEYWORDS

residual strength, colour, cracks, recuring, water cooling, water immersion, Rebound Index

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 (1). 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 (2) and (3) it is shown that both alterations can be linked to the residual strength since they are all function of the temperature. In this way it is possible to assess the temperature which the concrete has reached during the fire and to calculate the residual strength of the structure under investigation. In (4) and (5) the effect of the test conditions on the strength degradation is discussed: heating rate, time spent at target temperature and cooling method. (5) and (6) present a recovery of strength depending on the type of storage after fire. These parameters determine the actual residual strength and should be identified for doing a good analysis.

COMPRESSIVE STRENGTH REDUCTION

Table 1 gives the mix design of the self-compacting concrete (SCC) and the normal concrete with siliceous aggregates TC and calcareous aggregates TCk used in the 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). The heating rate was 3.5°C/min and the target temperature was kept constant for 750 minutes. The cubes were cooled in ambient air after removal from the oven. Fig.1 shows 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 curves for normal siliceous concrete [4].

CHANGE IN COLOUR AND POROSITY

At an age of 2 months two cores were drilled out of one 150 mm cube SCC and TC. 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) 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 coarse 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 (Fig.2a). In relation to the compressive strength, a peak is noticeable around 300°C corresponding to the development of a red tint (Fig.2b). The curves are similar for SCC and TC, but differences can be attributed to the greater amount of cement matrix for SCC.

For the macroscopic determination of the porosity, the surfaces were completely blackened and the pores and cracks were filled with white $BaSO_4$ powder. A picture was obtained by a flatbed scanner and analysed with the standard image processing programme ImageTool. Fig.3a presents the total porosity, given as the ratio of the white area to the black area, 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 (2) for Thames Valley aggregate concrete. SCC and TC have a different transition temperature, respectively 400°C and 200°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. Fig.3b gives the 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 (7), because they analyse pores with a smaller diameter than 50 micrometre, which is the minimum class detected with the flatbed scanner. In (2) and (3) 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.

TEST CONDITIONS

To determine the influence of the test conditions at the residual strength, TC and SCC 150mm cubes were heated up to 350°C and 550°C. The cubes were not preheated. Under standard test conditions the cubes were heated at a rate of 3.5°C/min, kept at the target temperature for 750 min and then cooled down in ambient air. One of these conditions is altered while the other remain the same as the standard. The heating rate is changed to 10°C/min for TC and 20°C/min for SCC. The duration at the target temperature was 3600min and the cooling regime was modified into a rapid cooling under water. Fig. 4 shows the effect of the different testing regimes on the residual strength (measured immediately after cooling). It seems that the cooling method is the most important parameter, resulting in an extra drop of the residual strength of 30-35%. Notice that the SCC cubes still have the 110% strength increase at 350°C, which was not the case in Fig.1.

RECURING

150mm cubes were heated according to the standard test regime at 350°C and 550°C, after which they were stored under water or in air for 7, 28 and 56 days. Fig.5 illustrates that the strength decreases to a minimum around 7-28days 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.

RELATIONS IN TIME OF COLOUR AND POROSITY

TC and TCk cubes are cut in two halves and heated to different temperatures according to the standard test conditions mentioned before. For each temperature level one half cube is stored under water (20±1°C) and the other half in air (RH 60% ; 20±1°C). The moisture absorption and the colour of the cube sides (concrete surfaces and a sawed side) are recorded during a period of 90 days. For TCk the colour change of the calcareous aggregates is also measured.

The colour change of the concrete surfaces is given in Fig.6 and the development of the colour of the calcareous aggregates is given in Fig.7. These measurements are done on the cubes stored in air. Again the elliptical path is clearly visible for the TC concrete surface and this alters a little bit for TCk. Notice that these concrete surfaces don't have colourful aggregates and that they are not polished. When concrete ages a shift of the colours can be seen towards the inner part of the elliptical path. This can probably be attributed to the moisture absorption, because a linear relationship between the colour change (L,a,b) and the weight increase can be found with a R^2 of 0.7-0.8.

Fig.8 shows the weight increase due to storage under water and in air. This increase in weight can be seen as a measure of porosity and shows a linear relationship (R^2 of 0.98 for $\theta \geq 200°C$) with the porosity determined on the polished samples as given in Fig.3. Two weight definitions are useful, this is the weight increase determined against the weight at

20°C for storage in air and the weight at 0 days (this is the weight shortly after fire) for storage under water. The method with the weight at 0 days is most promising, because here the reference weight is the investigated sample, preferably after drying. The method with the weight at 20°C requires a non heated reference sample obtained from a fired building and so knowledge about the differences in initial porosity and uncertainty of a non heated sample are then important. Storage under water of samples from a drilled core could therefore be a quick (saturation after 7 days) and cheap alternative to the method of polished samples.

SCHMIDT REBOUND HAMMER INDEX

The surface hardness of the previous samples is determined with the Schmidt Rebound Hammer for up to 90 days (Fig.9). The degradation till 7-28 days during recuring is not always present for the samples stored under water. The recovery of the surface hardness is greater for TCk than for TC. Differences in the recovery between storage under water and in air are clearly visible. Due to atmospheric effects (rain, sun), measurements on in-situ structures will be between the extremes given in the figure.

CONCLUSIONS

- Measurements of colour and porosity have a good potential for assessing the residual strength of concrete after fire exposure. An elliptical path in the a*b*-colour space can be noticed, which shifts to the inner part as a function of the moisture absorption.
- The influence of the heating rate and the time spent at the target temperature is small compared to the effect of rapid water cooling.
- A strength recovery is noticeable after a degradation of 7-28 days, but is still lower than the strength directly after cooling down to ambient temperature.
- Values of the Rebound Index sometimes show immediate recovery.
- Increase of weight due to storage under water is a good indicator for the amount of porosity and therefore the internal damage.

ACKNOWLEDGMENT

The authors would like to thank the Fund for Scientific Research in Flanders (FWO) for the financial support.

AUTHOR AFFILATION

E. Annerel. Research assistant, Ghent University, Magnel Laboratory for Concrete Research, Department of Structural Engineering, Technologiepark Zwijnaarde, 904, B-9052 Ghent, Belgium,
email: Emmanuel.Annerel@UGent.be - Phone: +32 9 264 55 19 - Fax: +32 9 264 58 45

L. Taerwe. Professor, Ghent University, Magnel Laboratory for Concrete Research, Department of Structural Engineering, Technologiepark Zwijnaarde, 904, B-9052 Ghent, Belgium,
email: Luc.Taerwe@UGent.be - Phone: +32 9 264 55 17 - Fax: +32 9 264 58 45

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TABLES AND FIGURES

Table 1 Concrete mix design

	SCC - siliceous	TC - siliceous	TCk - calcareous
sand [kg/m³]	782	640	663
gravel 2-8 mm [kg/m³]	300	525	-
gravel 8-16 mm [kg/m³]	340	700	-
limestone 2/6	-	-	450
limestone 6/20	-	-	759
portland cement I 52.5 [kg/m³]	400	350	350
water [kg/m³]	192	165	165
limestone powder [kg/m³]	300	-	-
superplasticizer [l/m³]	2.90	-	-
W/C [-]	0.48	0.47	0.47
compressive strength 28d [N/mm²]	65.9	56.5	60.3

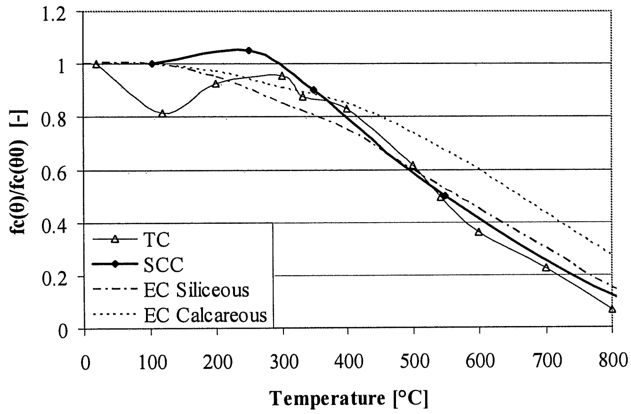


Fig. 1 Residual compressive strength

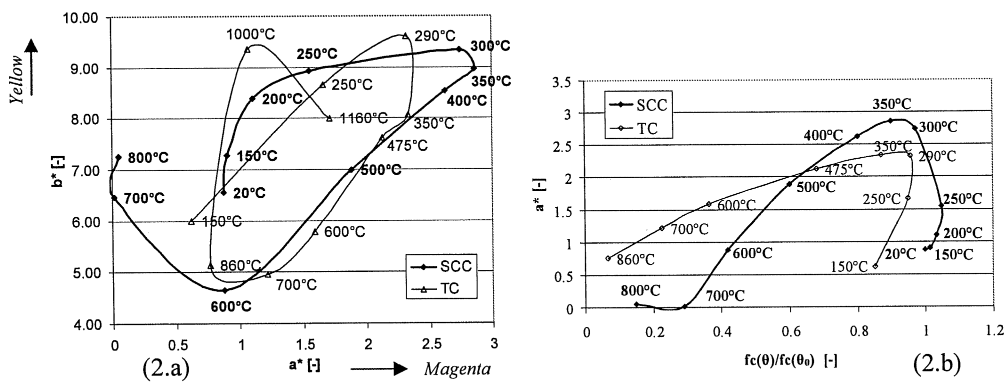


Fig. 2 (L)ab-measurements and relation to the compressive strength reduction

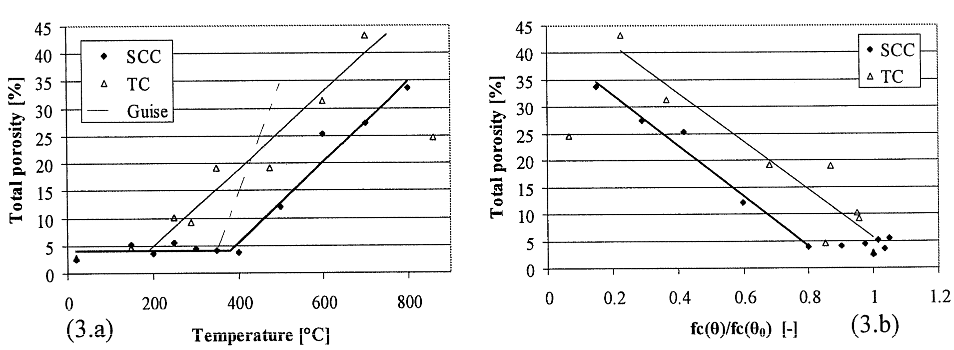


Fig. 3 Relation temperature – Total porosity – Strength decrease

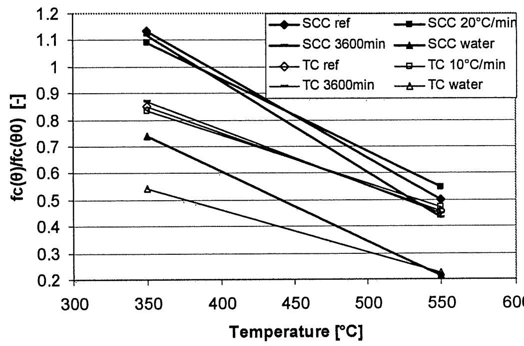


Fig. 4 Influence of different test conditions on the residual strength

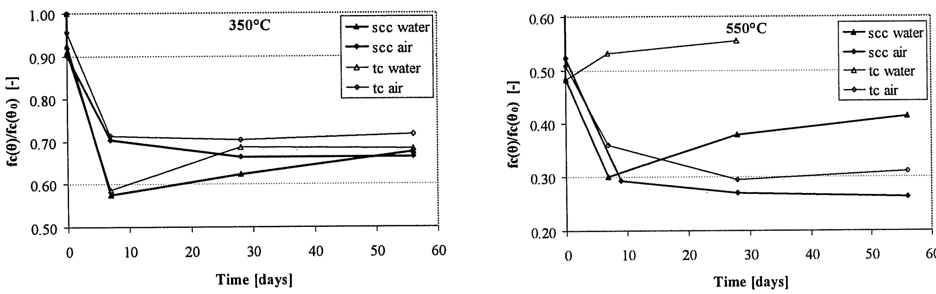


Fig. 5 Strength recovery during recuring

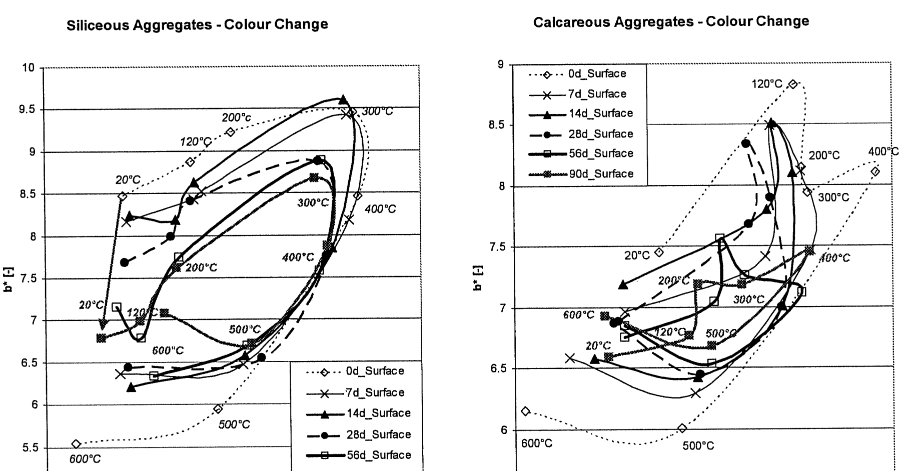
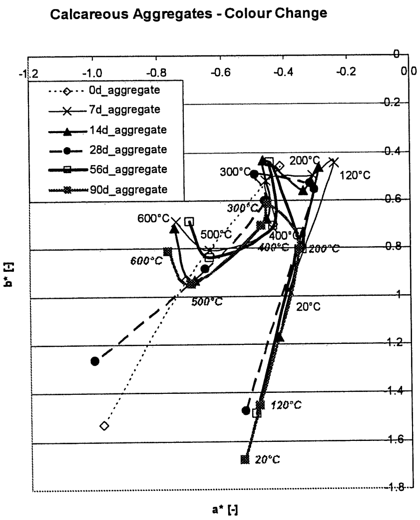


Fig. 6 Colour development at concrete surface as function of time



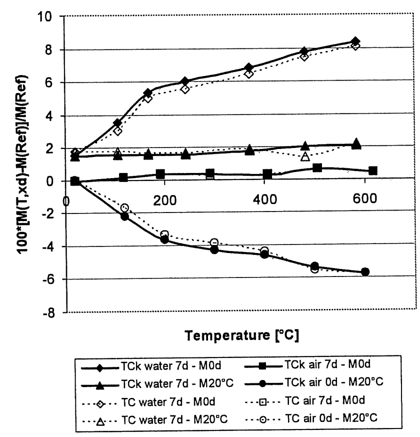


Fig. 7 Colour development of calcareous aggregate as function of time (Left)

Fig. 8 Moisture absorption (right)

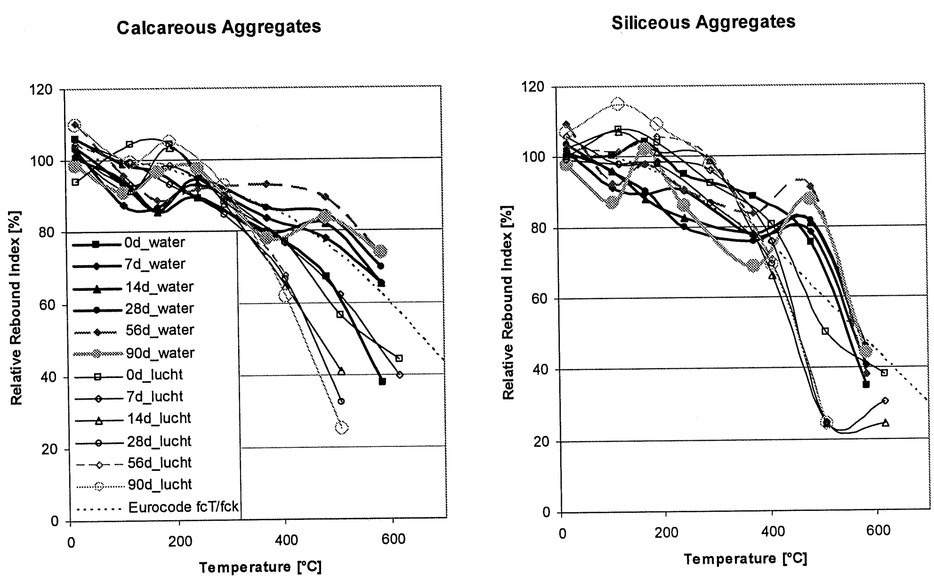


Fig. 9 Hammer Schmidt Relative Rebound Index