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TIME DEPENDENT BEHAVIOUR OF ULTRA HIGH PERFORMANCE FIBRE REINFORCED CONCRETE (UHPFRC)

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Abstract

Material characterization tests of a UHPFRC were performed at various ages. A linear relationship was obtained between the compressive strength and the degree of hydration. In parallel, the time dependent behaviour of this UHPFRC for different curing conditions was investigated. At a 20 °C temperature cure, the UHPFRC exhibited moderate autogenous shrinkage at long term with respect to normal concrete. An increase of curing temperature increased the autogenous shrinkage. This effect may be due to the hydration process and the self-dessiccation which are accelerated at high temperatures.
The effect of fibres on the autogenous shrinkage is also reported in this paper. The test results demonstrate that the presence of fibres decreases the autogenous shrinkage by 35% in comparison to the UHPFRC matrix without fibres.

Keywords

UHPFRC, degree of hydration, autogenous shrinkage, mechanical properties

1   Introduction

The outstanding properties of Ultra High Performance Fibre Reinforced Concretes (UHPFRC) make them very suitable for rehabilitation (Brühwiler et al. 2005), (Charron et al. 2004), (Habel 2004). However, the influence of different curing conditions on the UHPFRC early age behaviour, particularly when these materials are used as overlays on new or existing structures, and their sensitivity to premature cracking are still not completely understood.

The sensitivity to premature cracking of each material depends on the degree of restraint, the developement of the mechanical properties and the viscoelastic properties. Cementitious materials have a tendency to shrink due to various factors: evaporation of mixing water, the process of hydration and the removal of the adsorbed water from the layers of C-S-H. If this deformation is internally (due to rebar's, aggregates or fibres) or externally (due to existing concrete substrate or the rock) restrained in any way, the material can develop cracks at early age. This paper reports on a series of investigations on a UHPFRC material to determine: (1) the relationship between the degree of hydration and the mechanical properties, (2) the autogenous shrinkage for various curing conditions, (3) the influence of fibres on the autogenous shrinkage.

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2   Material

UHPFRC is produced by adding microfibres and straight steel fibres (10 mm/0.2 mm) to an ultra-compact cementitious matrix (cement CEM I 52.5, silica fume, fine sand with maximum size of 0.5 mm, water and superplasticizer). It contains a high volume of binder paste (0.88) with a very low water/binder ratio of 0.13. The UHPFRC of the CEMTEC$_{multiscale}$® family were originally developed at (Laboratoire central des ponts et chaussées) LCPC, (Rossi 2000) and have since been specially tailored at (Laboratoire de maintenance, construction et sécurité des ouvrages) MCS-EPFL for rehabilitation applications. The mixture proportions of the tested CEMTEC$_{multiscale}$® are given in Table 1.

Table 1 Mixture proportions

Material	[kg/m^3]
Cement / Silica Fume / Fine Sand	1410.2 / 366 / 80.4
Water / Superplasticizer	200.1 / 44.1
Steel Fibres (macro and micro)	706.5

3   Mechanical performance

Compressive strength and modulus of elasticity were tested using 11/22 cm cylinders, and modulus of rupture was measured by employing 4x4x16 cm^3 specimens subjected to three-point bending. The UHPFRC exhibits outstanding mechanical performance.

Figure 1a presents the compressive strength, the modulus of elasticity and the modulus of rupture (MOR) evolution with time. From the test results and the fitted CEB-FIP models, one can observe that the MOR and the elastic modulus tend to develop quicker at early age than the compressive strength. The MOR increased to 83 % of its 90 day value after 3 days, the modulus of elasticity increased to 90 % of its 90 day value after 7 days, and the compressive strength increased to 78 % of its 90 day value after 7 days. Thus the relative rate of development of the modulus of elasticity is higher than the rates of the MOR and compressive strength as observed by Lange (Lange 2002). This quicker rise in elastic modulus results in a built-up of tensile stresses, which may increase the early age cracking sensitivity.
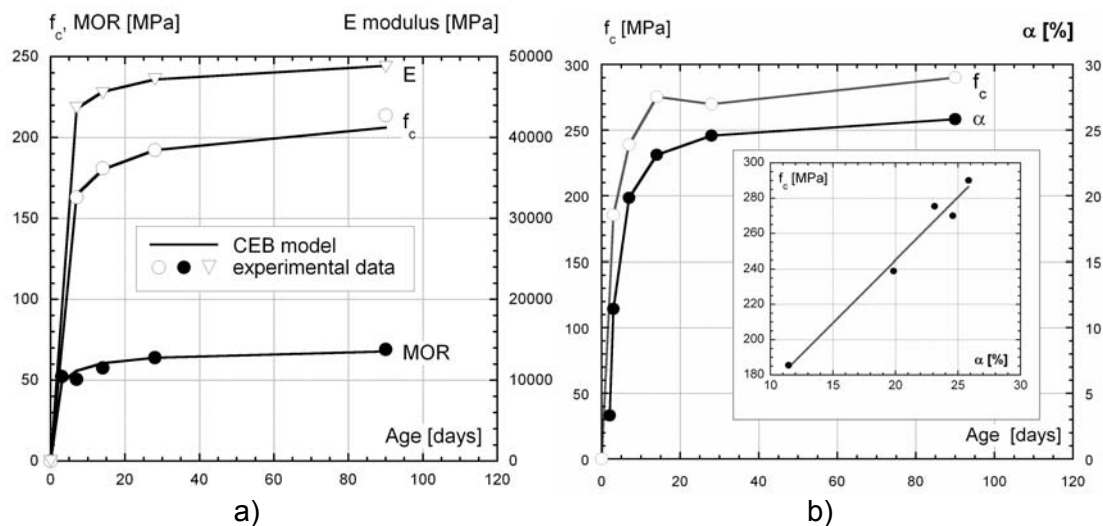

a)   b)

Figure 1 a) Mechanical properties as a function of time, and b) compressive strength correlation with degree of hydration

4   Degree of hydration

The degree of hydration was determined by loss on ignition using UHPFRC matrix (without fibres) samples. The employed procedure can be found in (Kamen et al. 2006).

The degree of hydration was calculated from the quantity of bound water (nonevaporable water). This procedure constitutes an indirect degree of hydration measurement by supposing a linear relationship between the amount of bound water and the degree of hydration as shown in (Copland and Kantro 1969), (Gutteridge and Dalziel 1990a, 1990b), (Parrott et al. 1990) and (Escalante-Garcia and Sharp 1998a, 1998b, Escalante-Garcia 2003)

The development of the degree of hydration α, shown in Figure 2 a, is fast at early age due to the heat produced during the hydration reactions and this heat further accelerates the hydration process.

The maximum degree of hydration calculated from the bound water is similar to the value estimated using the Powers model adapted by Jensen et al. (Jensen and Hansen. 2001). This model is based on the estimation of the closed degree of hydration (α_{max}) obtained as a function of the internal porosity and the matrix compacity which are each evaluated from the density of each matrix component, the water/cement ratio and the silica fume/cement ratio. This result is graphically shown in Figure 2 b.
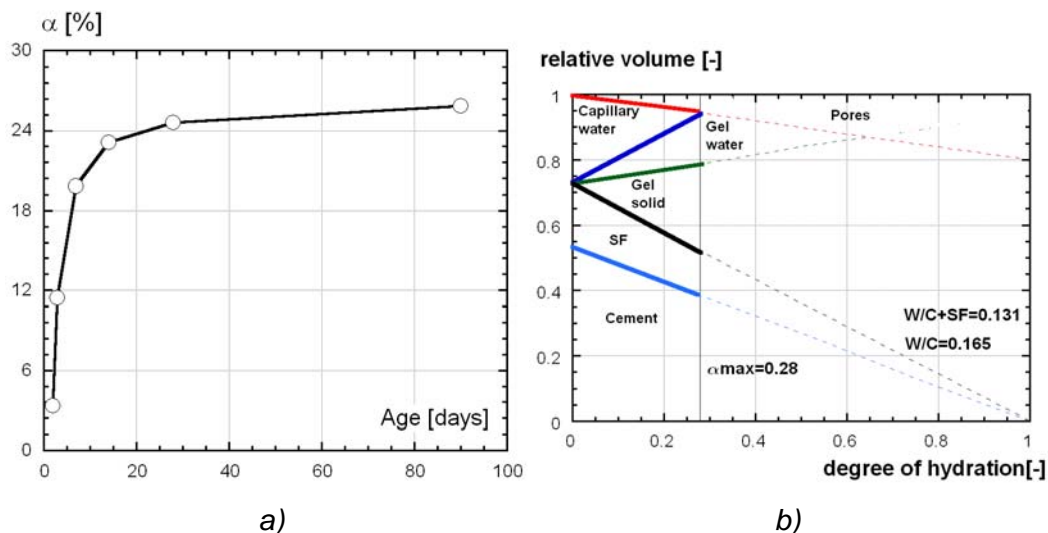

a)   *b)*

Figure 2 a) Degree of hydration as a function of time for a 20°C cure, and b) closed degree of hydration estimated by Powers model adapted by Jensen and Hansen.

5   Correlation between compressive strength and degree of hydration

Figure 1b, shows that the UHPFRC compressive strength development is closely linked to the hydration progress, similar kinetics are observed.

The development of the mechanical properties is accompanied by the change of material structure on the nano- and micro-scales and is related to the hydration process. The relationship between the degree of hydration and the strength can be described indirectly as the relation between the microstructure and the strength. A high strength is reached at low degree of hydration because this material is characterized by a low w/b ratio. This effect can be attributed to the initial dense packing of the cement particles which rapidly provides the small amount of gel required for bonding together the hydrating particles.

6   Autogenous shrinkage

The autogenous shrinkage tests were performed on sealed prisms 7x7x28 cm^3, in climatically controlled room with temperature of 20±2°C and RH of 65%, and starting at an age of 1.5 days.

Sealed conditions were implemented immediately after removing the forms, by applying double layers of self adhesive aluminium foil to prevent exchange with the external environment. The measurements were conducted by means of a rectractometer equipped with Tesa comparator, providing a measurement accuracy of about ± 5µm/m. The set up is shown in Figure 3a.

Table 2 Rate of autogenous shrinkage at 20°C

Age (days)	Rate[%]
3	23
7	39
28	60
90	85

The overall tests results confirm that this UHPFRC has a rapid kinetic of autogenous shrinkage. A value of 542 µm/m was obtained at 365 days for a 20°C cure. At 7 days, 39% of this value was reached, Table 2.

This quick autogenous shrinkage development at early age is attributed to the rapid hydration process, as shown before, the reduction of the internal relative humidity and the evolution of the microstructure resulting in a modification of the pore structure. This modification is associated with a decrease of the mean pore radius size and an increased capillary tension, leading to a large shrinkage of the solid skeleton.

One can observe that the rapid phase of autogenous shrinkage corresponds to the intense early age phase of desiccation, resulting from the rapid consumption of the available water during the hydration process. The rate of autogenous shrinkage diminished beyond 90days, Figure 3a, clearly shows also a stabilisation beyond 285 days.
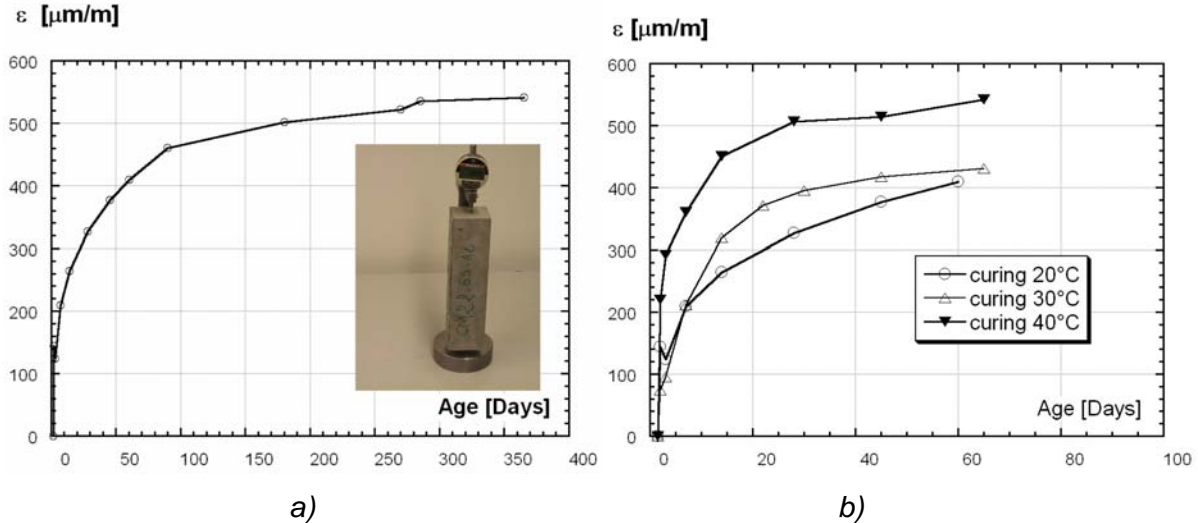

| a) | b) |

Figure 3 a) Long term autogenous shrinkage at 20°C as a function of time, and b) autogenous shrinkage for various curing temperatures

7   Influence of curing conditions on the autogenous shrinkage

The tests were performed on 7x7x28 cm^3 prisms, under various curing conditions (20, 30 and 40 °C), starting at an age of 1.5 days.

The curing temperatures (30 and 40°C) were imposed a few minutes after casting the UHPFRC. The forms were sealed in plastic foil and placed in the oven. After removing the forms, the same procedure of sealing employed for the specimens cured at 20°C, was applied to the specimens cured at 30 °C and 40°C.

The overall results demonstrate that the increase of temperature increases the autogenous shrinkage. For instance, an increase of about 5 % for 30°C and 32% for 40°C is obtained in comparison to shrinkage at 20°C, all measured at 65 days, Figure 3b.

At 7 days, 49% of the value measured at 65 days for a 30°C cure is reached, and 66 % of the value measured at 65 days for a 40°C cure is reached. In fact, the autogenous shrinkage practically halts beyond 28 days for specimens cured at 30 and 40°C due to the hydration evolution stabilisation, as illustrated in Figure 3b.

The influence of temperature on the autogenous shrinkage evolution is attributed to the hydration process and the autodessiccation which accelerates at higher temperatures, as shown in Figure 4.
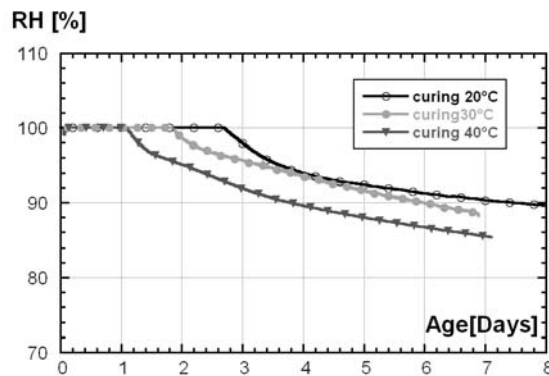

Figure 4 Relative humidity for various curing temperatures

8   Prediction of ultimate autogenous shrinkage

The model proposed by Loukili was used to estimate the ultimate autogenous shrinkage for various curing conditions (20, 30, 40 °C), (Loukili 1996).

8.1   Description of the model

Loukili has proposed an exponential function to extrapolate the measured values of autogenous shrinkage at infinite time.

The law proposed is of the form:

$$\varepsilon_{aut}(t) = A * \exp\left[\frac{B}{\sqrt{t+C}}\right] \tag{1}$$

where:
A, B, C: are parameters calculated by a minimisation process
t: time [days]
$\varepsilon_{aut}(t)$: autogenous shrinkage as a function of time [μm/m].

8.2   Ultimate autogenous shrinkage predicted from the model

Considering the ultimate values obtained from the model, rates of autogenous shrinkage of about 32, 35 and 56% are obtained respectively at 20, 30 and 40°C all at 7 days, as shown in Table 3.

One can observe in figure 5a that the highest ultimate autogenous shrinkage is obtained at 20°C. This result is in accordance with the evolution of the degree of hydration for different curing conditions obtained in our experiments. Indeed, the calculated degree of hydration from the loss on ignition test have shown that the hydration process is accelerated at early age for high temperatures but at long term a lower ultimate degree of hydration value is obtained. (Kamen et al. 2005)

However it necessary to verify the accuracy of the model for 30 and 40°C curing temperature by long term measurements.

Table 3 Rate of autogenous shrinkage for various curing conditions

Sealed, 7x7x28 cm specimens

Curing conditions		20°C	30°C	40°C
Starting of measurements		1.5 days	2 days	1.5 days
Autogenous shrinkage ε_{aut} [µm/m]	7 days	209.52	211.9	360.71
	65 days	415	430.95	542.86
Rate at 7days / ($\varepsilon_{aut-65days}$) [%]		50	49	66
ultimate autogenous shrinkage $\varepsilon_{aut-\infty}$ [µm/m]		661.48	605.30	640.99
Rate at 7days / ($\varepsilon_{aut-\infty}$) [%]		32	35	56

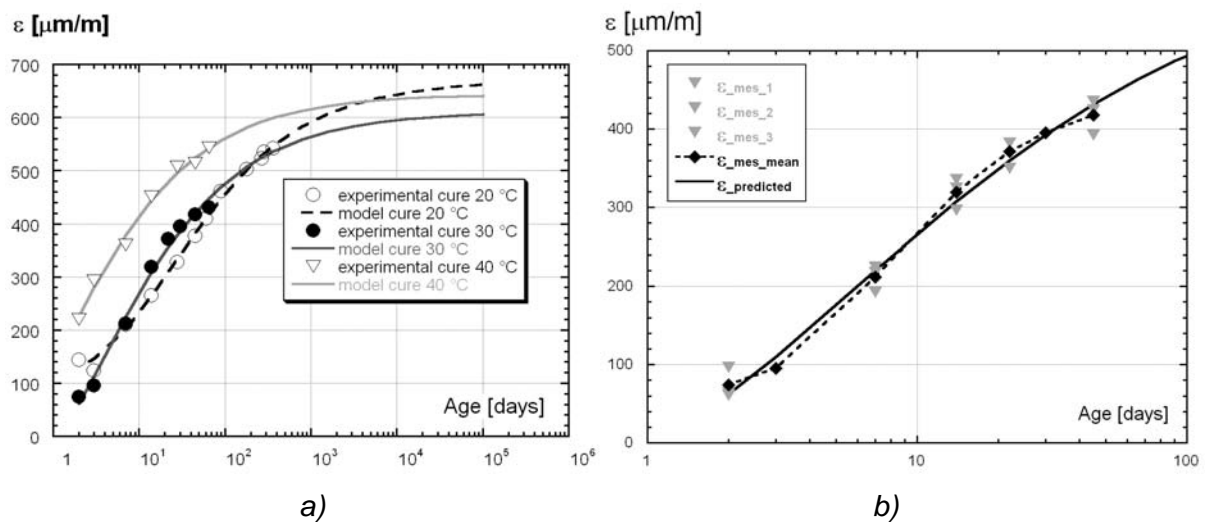a)   b)

Figure 5 a) The predicted autogenous shrinkage for various curing conditions, and b) detail of the predicted autogenous shrinkage at 30°C as a function of time

9   Influence of fibres on the autogenous shrinkage

The effect of fibres on the autogenous shrinkage was also investigated. The results demonstrate that the presence of fibres, decreases the autogenous shrinkage by 35% when compared to the matrix of UHPFRC without fibres as shown in figure 6, Indeed fibres can hinder the deformations to develop freely in the micro-level. This result confirms trends documented in literature for reactive powder concrete with lower amount of fibres. (Loukili 96), (Cheyrezy and Behloul 2001).
It was also demonstrated by Banthia that the use of fibres is very effective in reducing the widths of shrinkage cracks. (Banthia et al. 1995)
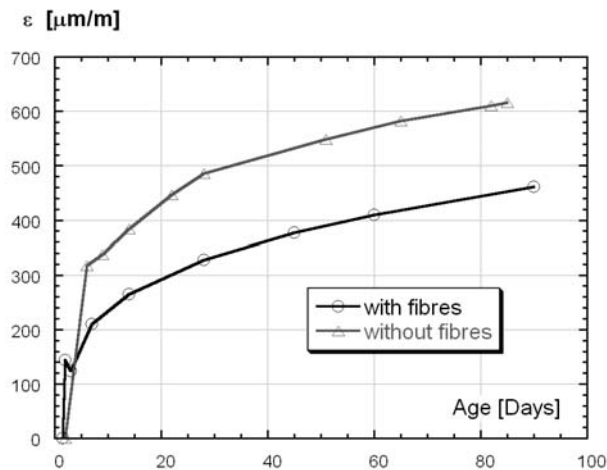
Figure 6 The influence of fibres on the autogenous shrinkage at 20°C as a function of time

10 Conclusions

A calculated degree of hydration of 26% at 90 days was confirmed by results obtained from the thermogravimetric test (not included in this paper) and by the application of the Powers model adapted by Jensen *et al.* (Jensen and Hansen 2001).

A strong correlation was found between the degree of hydration and the compressive strength.

The UHPFRC shrinkage was measured at early age and the dominant role of autogenous shrinkage was confirmed as demonstrated by (Habel 2004) and other authors for cementitious materials with low water/binder ratio.

Elevated curing temperature initially increased the rate of autogenous shrinkage. This result is in accordance with results published by other authors. (Charron 2003), (Bjontegaard 1999) and (Jensen and Hansen 1999).

In the long term, the predicted autogenous shrinkage was lower at temperatures higher than 20 °C.

11 Acknowledgements

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