Very early age Stiffness development of UHPFRC matrices in low temperatures

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Abstract

Very early age stiffness development of UHPFRC (Ultra High Performance Fiber Reinforced Concrete) matrix was evaluated under constant low curing temperatures. The Vicat Needle Test and Ultrasound transmission technique were performed as a conventional and as advanced method respectively for monitoring the setting phase of UHPFRC. Stiffness evolution of UHPFRC was monitored using Vibration Resonance Frequency (VRF) technique to investigate the development of UHPFRC dynamic elastic modulus. The results obtained under low temperatures of 5, 10°C and reference temperature of 20°C showed similar trend from the Vicat needle test, Vibration resonance frequency test and its corresponding temperature curve due to the heat of hydration while the Ultrasound transmission technique had significantly different response.

The outlook of this study is to establish accurate mechanical models that would help in forecasting the behaviour of structures rehabilitated using UHPFRC under real climatic conditions and give recommendations for their application.

1. Introduction

The use of prefabricated Ultra High Performance Fiber Reinforced Concretes (UHPFRC) members is rapidly developing worldwide in civil engineering structures. At the same time, the cast-on site application of thin layers of plain or reinforced tensile strain hardening UHPFRC in rehabilitation or reinforcement of existing structures has demonstrated its technical and economical efficiency in various applications in Switzerland and Slovenia [1, 2]. However contrarily to prefabrication, cast on site UHPFRC are subjected to mechanical restraint from the existing substrate which induces high eigenstresses that could compromise the excellent protective functions of the UHPFRC, i.e. its very low permeability.

One of the major factors influencing the cracking potential of cementitious materials such as UHPFRC is the rate of development of their mechanical properties at early age: stiffness (modulus of elasticity), viscous response, tensile strength and deformation capacity (strain hardening). Further, the influence of the climatic conditions during and after casting on the development of free deformations and eigenstresses in UHPFRC at early age is still an open subject [3], barely studied for low temperatures (5 to 20°C).

The objective of this paper is to investigate how curing in low temperatures would affect the rate of stiffness development of UHPFRC at very early age. Also the start of self-desiccation and divergence of autogenous shrinkage and chemical shrinkage, i.e. time t_o has been considered approximately to be the setting time, therefore a close estimate of the initial and final setting time of UHPFRC would assist in knowing when the mentioned phenomena initiates.

The expected outcomes of this research are threefold: (1): Obtaining information on the effect of low temperatures on the stiffness development of UHPFRC (setting time and elastic modulus) which will assist in assessing the potential of localized cracking, (2): Use of the elastic modulus development data in modeling the early age behavior of UHPFRC (free deformations and Eigenstresses), (3): Defining suitable range of temperatures for UHPFRC application on site and assist in knowing the time frame for placing, finishing, and start of curing.

Three types of tests have been performed on the matrix of a tensile strain hardening UHPFRC mix developed for rehabilitation applications, at three different constant curing temperatures (5, 10, 20°C):

1. Evaluation and comparison of the evolution of very early age elastic modulus of UHPFRC matrix using vibration resonance frequency test.
2. Vicat needle test as a conventional method and ultrasound transmission method as an advanced method to obtain reliable estimation of the setting time of UHPFRC matrix.
3. Simultaneous measurements of the temperature evolution in companion specimens for each test method.

2. Materials and test program

For the research presented here a UHPFRC of the CEMTEC $_{\text{multiscale®}}$ type developed at LCPC by Rossi et.al [4] was used. The matrix + microfibers of recipe CM22 tailored at MCS-EPFL for rehabilitation applications has a 1410 kg/m^3 Cement CEM I 52.5, water to binder ratio of 0.131, Microsilica of 366.6 kg/m^3, fine sand D_{max}=0.5 mm of 80.4 kg/m^3 and steel wool and 2.3 % superplasticizer. Further information about the UHPFRC recipe used can be found in [5].

A 20 litre planetary paddle mixer by Hobart was used for mixing the UHPFRC matrix. Initially Cement, microsilica and Steel wool were mixed for a time interval of 2 minutes. Then sand was added and the mixture was mixed for 30 seconds. Finally the water and superplasticizer were added and entire mixture was mixed for approximately 6 to 8 minutes.

The experimental program comprised of the Vicat needle test, vibration resonance frequency test and ultrasonic transmission technique. The constant curing temperatures investigated were 5, 10 and 20oC. For each curing temperature the experimental program was executed two times to insure the repeatability of the results obtain from each test. Each time, one sample in each experiment was used to monitor the evolution of temperature due the exothermic hydration reaction while the other sample was used to measure the associated material property.

3. Experimental methods

3.1 Vicat needle testing apparatus

The automatic Vicat needle E040 apparatus was used per ASTM C191-08 [6] as a conventional method to obtain the setting time of UHPFRC matrix. The UHPFRC was cast in a conical mold having dimensions of 60/70/40 mm. A calibrated weight of 300 g and a cylindrical needle with flat tip area of 1 mm^2 were used. Within this study, depending on the curing temperature, appropriate timing was chosen to start the apparatus to automatically perform 41 penetrations at regular time intervals. The elapsed time between initial contact of cement and water and the time when the penetration was 25 mm is considered to be the initial set and the elapsed time between initial contact of cement and water and the time when the needle does not leave a complete circular impression on the paste surface is considered to be the final time of setting.

3.2 Ultrasonic transmission technique using FRESHCON

The Ultrasonic transmission technique using the FRESHCON [7] device was employed as an advanced method to monitor the setting time of UHPFRC matrix by measuring the development of Ultrasonic Pulse Velocity (UPV) within the UHPFRC matrix as it changes from a liquid suspension to a solid porous network.

In the transmission method used, two P-wave piezoelectric transducers are connected on each side of the PMMA mold. The mold with a 45 cm^3 volume is filled with the UHPFRC matrix. A pulse width of 2.5μs is generated using a broadband frequency generator, an amplifier and then transmitted by the piezoelectric transducer. The longitudinal wave propagates through the material and the receiving transducer receives the propagated wave and sends it to the DAQ card. The wave gets recorded, digitized and stored in the computer. The transit time t was then determined first by manual picking for a better accuracy during the early stages after casting, and later automatically using the Akaike Information Criterion (AIC) option provided by the FRESHCON Software By obtaining the transit time t for each signal and knowing the path length L (width of the mold= 22mm) the wave velocity for each signal could be calculated as:

$$v = {}^{L}\!/_{t} \qquad \text{EQ (1)}$$

3.3 Vibration resonance frequency test

The vibration resonance frequency test was used to assess the development of dynamic elastic modulus of the UHPFRC matrix. A steel ball with 1 cm diameter was used to hit the centre of one of the circular faces of a standard test cylinder (4 by 8 inches - 11 cm x 22 cm) to provide the excitation. At the opposite face of the cylinder a miniature accelerometer is attached having a central resonance frequency of 70 KHz which captures the longitudinal wave after propagating through the UHPFRC matrix. The captured wave after passing from the accelerometer's signal conditioner was then digitized by a high speed USB DAQ module. Finally a LabVIEW program read, registered the signal in time domain and then converted the signal to FFT domain to obtain the 1st and 2nd resonance frequency of the cylinder from the frequency spectrum. The mass of the cylinder containing UHPFRC matrix, was also measured to obtain its density. After having the 1st and 2nd longitudinal resonance frequencies and the mass of the cylinder, the mathematical expressions for obtaining the dynamic elastic constants of the UHPFRC matrix are given in equation set 2 based on [8]. Detailed information regarding this test setup can be found in [8].

$$\mu = A_1\left(\frac{f_2}{f_1}\right)^2 + B_1\left(\frac{f_2}{f_1}\right) + C_1 \qquad E = 2(1+\mu)\rho\left(\frac{2\pi R_o f_1}{f_n^1}\right)^2$$

$$f_n^1 = A_2(\mu)^2 + B_2(\mu) + C_2$$

$$A_1 = -8.6457\left(\frac{L}{D}\right)^2 + 24.4431\left(\frac{L}{D}\right) - 12.4778 \qquad A_2 = -0.2792\left(\frac{L}{D}\right)^2 + 1.4585\left(\frac{L}{D}\right) - 2.1093 \qquad \text{EQ (2)}$$

$$B_1 = 34.5986\left(\frac{L}{D}\right)^2 - 101.7207\left(\frac{L}{D}\right) + 56.172 \qquad B_2 = 0.0846\left(\frac{L}{D}\right)^2 - 0.5868\left(\frac{L}{D}\right) + 1.3791$$

$$C_1 = -34.6807\left(\frac{L}{D}\right)^2 + 105.979\left(\frac{L}{D}\right) - 62.731 \qquad C_2 = 0.285\left(\frac{L}{D}\right)^2 - 1.7026\left(\frac{L}{D}\right) + 3.3769$$

where f_1 and f_2 are the frequencies of the first and second longitudinal modes of vibration (in Hz), R_o is the radius of the solid cylinder (in meters) and ρ is the density of concrete (in kg/m^3).

4. Results & Discussions

Figure 1 shows the development of the penetration resistance of the UHPFRC matrix measured using the Vicat needle testing apparatus for 5, 10 and 20°C and their corresponding temperature evolution due to the heat of hydration in the mold. It can be seen that as the curing temperature decreases there is a larger delay in the penetration resistance build up of the UHPFRC matrix and consequently in the setting time. Furthermore the final setting time roughly corresponds to the very early beginning of the temperature rise due to the heat of hydration. Table 1 shows the average setting time values obtained from four samples for each curing temperature using the Vicat needle test. There exists a time span difference in the setting times between 10°C-20°C and 10°C-5°C. There are differences of 4.5 and 5.1 hours between the initial and final setting time of 10 and 20°C curing temperatures while these differences increase to 6.7 and 7 hours in case of 10 and 5°C. Finally it should be noted that there is a scatter between the samples having the same curing temperatures.

Table 1: *Setting time values (in hours) obtained from Vicat needle test for 5, 10 & 20°C*

	20°C	10°C	5°C
Initial Set	*22.3*	*26.8*	*33.5*
Final set	*24.0*	*29.1*	*36.1*

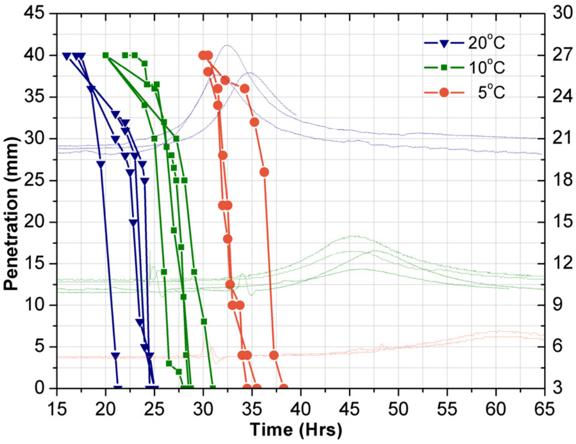

Figure 1: *Development of penetration resistance obtained from Vicat needle test*

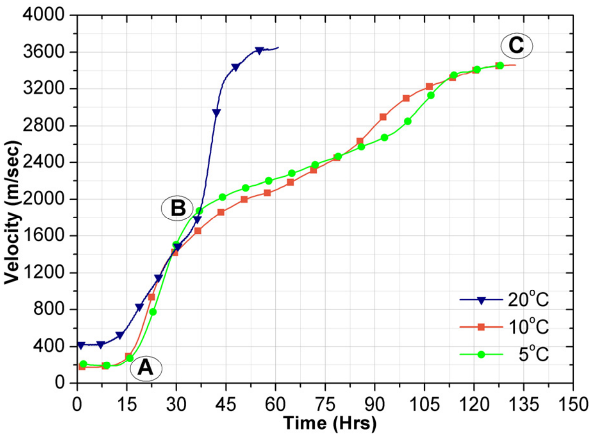

Figure 2: *Influence of curing Temperature on UPV, average curves*

Figure 2 shows the velocity development of the longitudinal wave within the UHPFRC matrix using the ultrasound transmission technique, for 5, 10 and 20°C curing temperature conditions. The S-shape curve can be categorized into three distinct segments [9]. In the first part, there is no change in velocity. The second segment starts with a slow increase in velocity (point A) followed by a linear increase as the hydration products are formed; the second segment ends by reaching a knee point (point B). The third segment starts thereafter with another linear increase in velocity but with a different slope. As more and more of the hydrated particles are connected to each other, the ultrasonic pulse propagates through more connected solid volume. However by the time a fully connected solid frame is made, the velocity does not increase significantly (point C). It is interesting to note that approximately until the knee point, effect of the curing temperature on development of velocity is minimum;

in other words, for all the curing temperatures, until the knee point B, the development rate of the hydration products was not influenced by the curing temperature. It is only during and after the setting that the velocity development becomes apparent in specimens with different curing temperatures. After the knee point, the rate of velocity increase is much faster in 20°C than in 5 and 10°C. Further investigation is needed to confirm the experimental results, and understand the underlying phenomena

Figures 3 and 4 show the development of dynamic elastic modulus obtained from VRF test for 5, 10 and 20°C with their corresponding temperature evolution due the the heat of hydration in the cylinders. It could be seen that all curves regardless of the curing temperature conditions have an S-shape look associated with their dynamic elastic modulus development. Samples cured at higher temperature, had higher rate of dynamic elastic modulus development. Furthermore the first values of dynamic elastic modulus obtained in each samples correspond approximately to the start of the temperature rise.

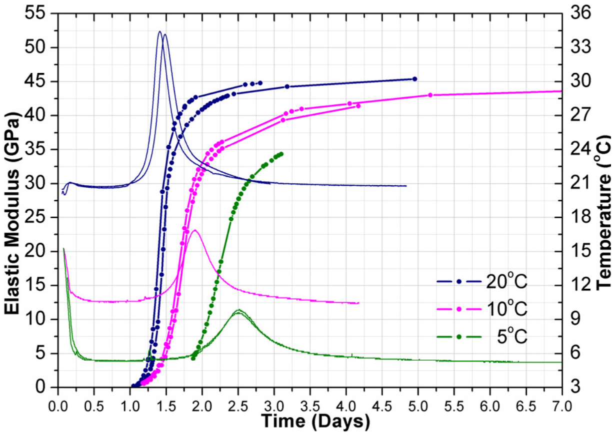

Figure 3: *Development of Dynamic elastic modulus from VRF test for 5, 10 and 20°C*

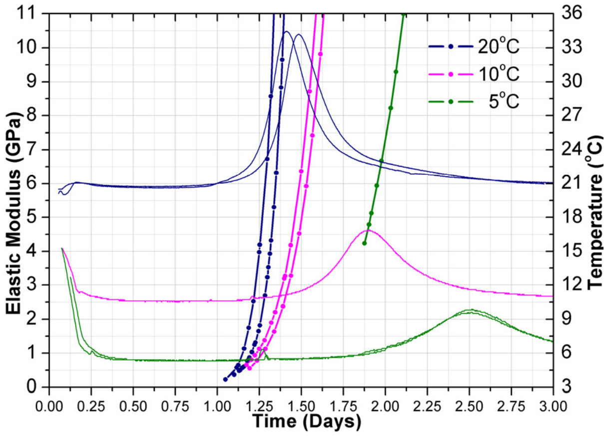

Figure 4: *Close up view of figure 3 at early age*

From the results obtained, it appears that the final setting time from the Vicat needle test correlates to the start of dynamic elastic modulus development, and very early temperature rise due to the heat of hydration. The mentioned specific point from each test gives an approximate estimation of time t_o i.e. the time at which Eigenstresses start to develop in the UHPFRC if it is restrained.

The results from the VRF test showed that as the curing temperature goes down, the development of elastic modulus slows down. Furthermore the general trend in Vicat needle test, VRF test and the development of temperature due to heat of hydration showed that as the temperature goes down, there is a delay on evolution of the material properties associated with each test while this trend ceases to be valid in case of velocity measurements obtain from the FRESHCON system.

5. Conclusions and outlook

- The final setting time from the Vicat needle test correlates well to the start of dynamic elastic modulus development from VRF tests, and very early beginning temperature rise due to the heat of hydration.
- Thus, an estimation of time t_o (the time at which Eigenstresses are initiated in the UHPFRC matrix if it is restrained) can be determined as a function of temperature (in isothermal conditions) within a range of 2 hours.

- The VRF test provides very accurate and detail information on the effect of low curing temperature on slowing down the development of the elastic modulus. These results will be used in a further step to model the development of free deformations and Eigenstresses in the UHPFRC.
- Velocity measurements with the FRESHCON system for different temperatures showed two different trends. After setting, the rate of velocity increase was significantly influenced by the curing temperature, while it was similar for all temperatures before setting. The later was unexpected and will be further investigated.

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