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NDT TESTING OF STIFFNESS EVOLUTION OF UHPFRC SINCE CASTING

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ABSTRACT

The current work presents the continuous monitoring of the early stiffness evolution of an UHPFRC (Ultra-high performance fibre reinforced cement composites) mixture using a combined set of non-destructive testing techniques; "Elasticity Modulus Measurement through Ambient Response Method" (EMM-ARM), Ultra Sound Pulse (UPV) velocity measurement, and resistivity measurement. Three mixture proportions are considered for all testing techniques, covering a reference mixture without added fibres and a couple of mixes with 1.5% and 3.0% of fibres, respectively. Conclusions are taken in regard to the particularities of stiffness evolution in UHPFRC in view of the particularities of the material (namely the presence of fibres).

Keywords: Ultra-high performance fibre reinforced composites (UHPFRC); EMM-ARM; E-modulus; early ages.

1. INTRODUCTION

Ultra-high performance fibre reinforced composites (UHPFRC) exhibits remarkable mechanical properties (compressive strength >150 MPa and tensile strength >7 MPa), it can exhibit strain hardening in tension and extremely low water permeability [1]. These outstanding properties made up the idea to use UHPFRC to rehabilitate and strengthen zones of the existing reinforced concrete structures (RCS), namely, in areas exposed to severe environmental conditions (as de-icing salts, marine environment, chemical attack) and high mechanical loading (e.g. concentrated forces, wear, fatigue, impact). This technique has been successfully applied towards the fulfilment of this objective [2], [3], [4]. UHPFRC, which presents a low water binder ratio (<0.22) and contains high fineness additives without any coarse aggregate (1 mm of maximum size), is prone to development of high autogenous deformations at a very early ages. Autogenous shrinkage reduces the compressive strength and can lead to the development of high tensile stresses in the new layer of UHPFRC [5], [6], [7], which deformations are restrained by both the existing support and reinforcement bars in the UHPFRC (if any). Nevertheless, the magnitude of the internal stresses is influenced not only by the shrinkage rate and magnitude, but also by the development of material properties during the first ages, namely, tensile creep, the evolution of the young modulus and strength. Therefore, the very early age strength and elastic modulus of UHPFRC should be measured and predicted in order to control the possible premature shrinkage cracks in practical applications.

The measurement of stiffness in cementitious materials is for several years a big challenge to the scientific and technical communities especially with regard to the early ages monitoring [8]. Several distinct methodologies have been proposed throughout the years that allow more or less direct assessment of stiffness or stiffness-related properties. Resonant frequency methods are commonly used to assess the E-modulus of cementitious materials. Usually they are based on the use of longitudinal, transversal and torsional waves, but flexural waves may be adopted as well [9]. A variant to these methods was developed by Azenha et al. [10], the Elasticity Modulus Measurement based on Ambient Response Method (EMM-ARM), which allows continuously monitoring the E-modulus evolution of cement-based materials since casting. EMM-ARM is based on the identification of the resonant frequency of the testing mould (hollow cylinder in simply supported conditions, inside which the sample to be tested is cast), which evolves along time due to the hardening process of the tested material. By monitoring the accelerations of the composite beam at mid-span, it is possible to perform the modal identification and to evaluate the first flexural resonance frequency of the beam. The E-modulus of the tested material can then be inferred with basis on the dynamic equations of motion of the testing system.

Non-destructive tests (NDT) based on acoustic emission and electrical resistivity techniques are well suited for the study of cementitious materials early-age development since the physical properties they measure change during the curing process. Moreover, the conventional test methods for measuring setting (like Vicat test) and strength properties cannot evaluate the physicochemical and microstructural changes that continuously occur in cementitious materials. Thus, several efforts have been made to examine the setting development using ultrasonic pulse velocity (UPV) measurements since this method is able to consistently evaluate the microstructural changes in cementitious materials. As the hydration goes on, ultrasonic pulse propagation path in the cement system switches from the liquid phase to the solid phase. At early times

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the observed wave involves essentially motion of the fluid phase while at later times it involves essentially motion of the solid frame. Thus, Ultrasonic waves are therefore sensitive to the point at which the solid phase becomes interconnected. [11]. Concerning electrical resistivity method, the electrical conduction of cement-based media relies on ionic conduction through water-filled pores. The factors influencing electrical conduction for porous media are mainly controlled by microstructure and liquid solution conductivity. Previous research has shown that electrical measurements can be applied to provide useful information of the hydration process of the cement-based materials [11]. In addition, NDT methods are also useful to compare the effect of the various mix components in the hydration process.

For this purpose a specimen curing apparatus was developed in laboratory to assess, simultaneously, ultra-sonic pulse velocity (UPV) and resistivity evolution since casting of UHPFRC specimens. Young Modulus was assessed using EMM-ARM in similar mixtures. Additionally, mechanical strength at 7 days was evaluated.

2. EXPERIMENTAL PROGRAM AND RESULTS

2.1 Materials Characterization, mix proportions and testing procedures

The materials used in this study were Portland cement Type I 42.5R (specific gravity of 3.11 g/cm^3), silica fume supplied in suspension (specific gravity of 1.38 g/cm^3 and solid content 50%), limestone filler (specific gravity of 2.68 g/cm^3), siliceous sand (1 mm maximum aggregate size, specific gravity of 2.57 g/cm^3 and water absorption value of 0.02% not considering the fine particules). A polycarboxylate type superplasticizer (Sp) having specific gravity of 1.08 g/cm^3 and 40% solid content was used. The mixtures produced were: i) a reference mixture – UHPC (without fibres) - and ii) two fibre reinforced mixtures– UHPFRC 1.5% and UHPFRC 3.0% –with incorporation of 1.5% and 3.0% of steel fibres, by volume, respectively. The mixture proportions are listed in Table 1. Mortar flow test was carried out to evaluate the mixtures in the fresh [12], spread flow (Dflow) results are presented in Table 1. Prismatic specimens (40x40x160 mm^3) were produced, which after demoulding in the following day were cured in water at 20 °C, and tested to assess compressive strength at 7 days (Rcm,7d) , according to NP EN 196-1 [13] (see Table 1).

Table 1 - Mixture compositions of UHPFRC.

		UHPC	UHPFRC	UHPFRC 3.0%
Binder	Cement (c)	794.90	794.90	794.90
	Silica fume (sf)	79.49	79.49	79.49
Aggregates	Sand	1019.86	981.31	942.76
	Limestone Filler (f)	311.43	311.43	311.43
Water		153.76	153.76	153.76
Superplasticizer		20.00	25.00	25.00
Fibres		-	117.75	235.50
Ratios	w/c	0.22	0.22	0.22
	Sp/(c+sf+f) (%)	1.69	2.11	2.11
	Fibre factor - χ*	-	0.90	1.80
Fresh state	Dflow (mm)	275	290	261
Setting	Final Setting time (hh:mm)	02:40	02:15	02:15
Compressive strength	Rcm,7d (MPa)	87.8	116.0	126.8

$*\chi = \frac{Vf \times Lf}{df}$, where Vf is the volume of fibres per m^3, lf and df are the length and diameter of fibres, respectively.

2.3 Ultrasound pulse velocity and electrical resistivity measurements

A laboratory prototype was developed to enable the continuous testing of the composite immediately after mixing. It consists of a cubic box (100mm) instrumented in the bottom face with a temperature sensor (PT100), connected to an automatic acquisition system (see Figure 1). In this prototype the material (plywood) surrounding cement samples avoided rapid dissipation of heat to the environment. In addition, stainless steel networks were embedded in two of the lateral walls of the samples to work as electrodes, allowing assessing resistivity evolution over time, by using the two electrodes technique. The signal generator performed a SIN wave, voltage of ±10V and frequency of 100Hz. The other two lateral walls were prepared to fit the ultrasonic pulse velocity (UPV) probes in close contact with the sample and thus allowing also to evaluate the UPV evolution with time. P-wave transmission was performed by Proceq TICO, an ultrasonic portable instrument, through two transducers of 54 kHz, with a voltage pulse of 1000V and 0.1 µs of resolution. It should be noted that it is very difficult to determine the transmission time of fresh pastes, especially before the setting of cementitious materials because the ultrasonic wave has a great attenuation in plastic cementitious pastes, resulting in an obvious disturbance from the noise of the signal. For this reason, UPV measurement started approximately 2 hours after mixing. Figure 3 shows resistivity evolution of the three mixtures produced and UPV evolution is presented in Figure 4, as well as, temperature evolution.

Figure 1. Setup for Ultrasound pulse velocity and electrical resistivity measurements: a) pc; b) DataTaker; c) electrical cable connection for temperature measurement; d) polywwod cubic box; e) transducers; f) electrodes

2.3 Elasticity Modulus Measurement through Ambient Response Method

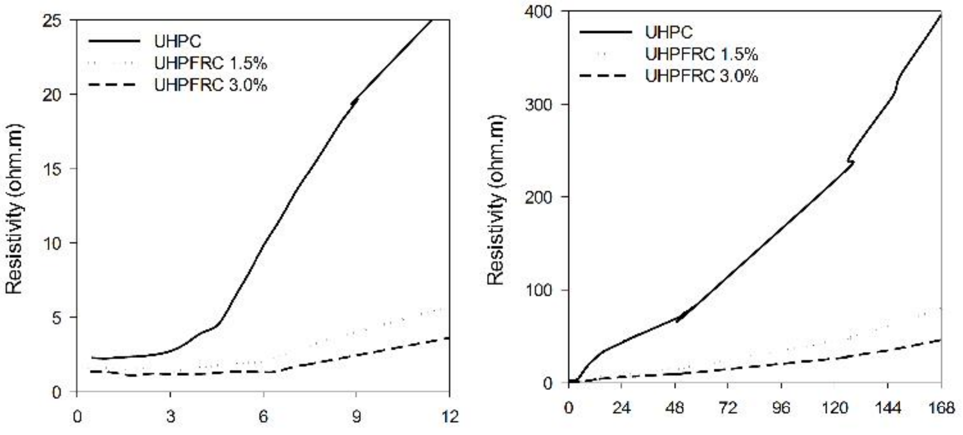
The EMM-ARM was applied to UHPFRC, using a plastic tube mould with 550 mm long and external/internal diameters of 50/44 mm. This configuration, shown schematically in Figure 2, allows the structure to behave as a simply supported beam with a free span of 500 mm. A custom electromagnetic actuator, developed by Granja [14], was specially designed to be able to apply a very small dynamic force to the testing beam without physical contact between the actuator and the beam. A representation of this custom made electromagnetic actuator is shown in Figure 1 a). The force is applied to the beam through a magnet that is physically attached to the bottom of the beam at mid span. On the opposite side, the magnet is surrounded by a coil. When subjected to a given current intensity, this coil creates a magnetic field dependent on the current polarity and intensity. The coil's frame was built in a non-ferromagnetic material (plastic) to prevent interaction between the magnet attached to the beam and the body of the actuator, which could again introduce an effect similar to that of an elastic spring at mid span of the beam. Regarding the test procedure with forced excitation, a sine function was sent in a continuous sweep of frequencies with 40 seconds duration between 20 and 200 Hz with an amplitude of ±2.4 V, through a dynamic signal analyser NI 4431 with 24-bit resolution, at a sampling frequency of 20 kHz. The induced accelerations were measured using a piezoelectric impedance sensor (PCB 288D01 with sensitivity to accelerations of 100 mV/g in the range of reading ±50 g and sensitivity to forces of 22.4 mV/N in the range of reading ±222.4 N) [14]. Results of Young Modulus evolution are present in Figure 5.

a) b)

Figure 2. a) Schematic view of custom made non-contact electromagnetic actuator attached to an EMM-ARM beam [units: mm] [14]; b) EMM-ARM beam.

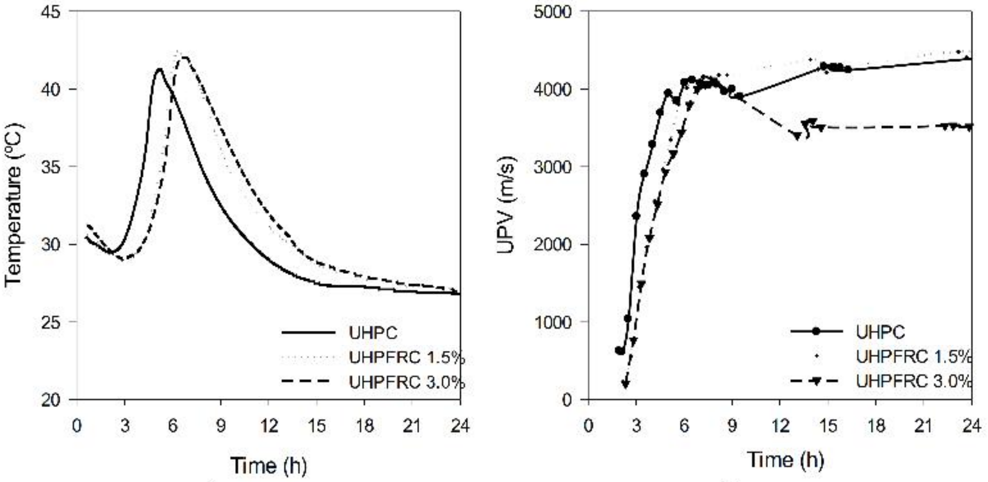
3. DISCUSSION

Generally, with the addition of steel fibres, the flowability of UHPFRC decreases [15], [16]. As can be seen in Table 1, for the same amount of superplasticizer in mixes with 1.5% and 3.0% of steel fibres, the UHPFRC 3.0% flow diameter decreased compared to UHPFRC 1.5%. In order to account for the combined influence of fibres aspect ratio and fibre content a parameter called the fibre factor (χ) can be used [17], which is also presented in Table 1. A small value of fibre factor (<1.0) has little influence on final spread diameter, while higher fibre factor (>2) increases the risk of fibre agglomeration during the mixing process and decreases workability [18]. Fibre factors were below 2, thus no significant loss of workability was observed.



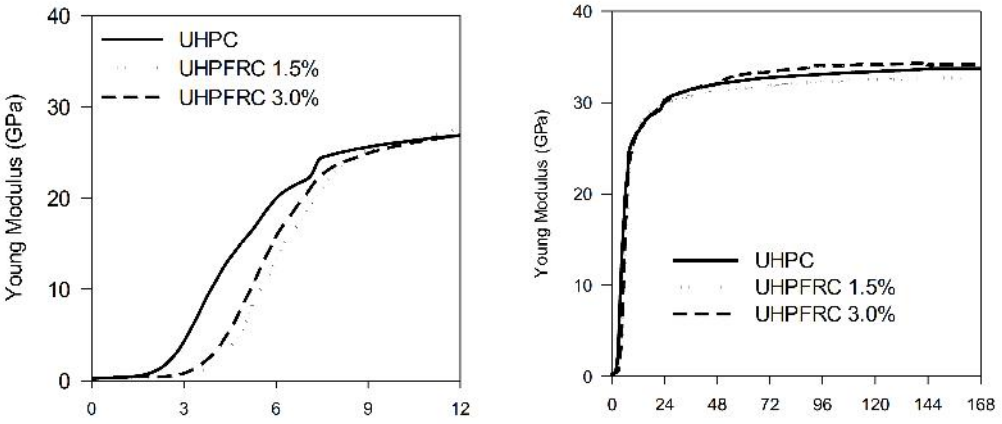
a) b)

Figura 3. a) Resistivity evolution up to 24 hours; b) Resistivity evolution up to 168 hours.



a) b)

Figura 4. a) Temperature evolution up to 24 hours; b) UPV evolution up to 24 hours.



a) b)

Figura 5. a) Young Modulus evolution up tp 24 hours; b) Young Modulus evolution up tp 168 hours.

According to Zhang et al [11], on first contact with water, the mobile ions are rapidly released from the surface of each cement grain; the pH values rise to over 12 within a few minutes, which is called hydrolysis. Due to the ion dissolution, the conductivity of cement–water mixture will increase and the resistivity decreases inversely. After reaching the saturation, this initial hydrolysis slows down quickly, which is corresponding to the minimum point in the resistivity. Then, in the next stage, almost no evolution of resistivity occurs which means that the mixture is relatively inactive, which refers to a competition between the dissolution and precipitation, identified as a dynamic balance, or called competition period [19]. After this stage, the resistivity increases rapidly. With hydration degree increase, the resistivity of the sample increases due to the growing solid phase and their interconnection, which will block the way of transportation of the ionic conductors in the pore solution. This increase continues through the whole test period [11], [19]. Figure 3 shows the electrical resistivity development with time up to 7 days (168 h). UHPC resistivity-time curve begins with a slight decline, corresponding to the period up to approximately 1h, 1h30 and 3h after mixing, for UHPC, UHPFRC 1.5%, UHPFRC 3.0%, respectively. This stage corresponds to the dissolution of ions from cement into water (stage 1). Then, the resistivity of the specimens increases slightly for several hours, stage 2, up to about 4h for UHPC. With the inclusion of steel fibres the mixes became very conductive, consequently, lower values of resistivity were achieved.

As stated previously UPV measurements started 2h after mixing and at this time, a period of rapid increase of the UPV occurred, which corresponds to the end of dormant period and rapid development of hydration products, see Figure 4-b. This period started at the similar time as that of stage 2 in resistivity evolution. When a critical quantity of hydration products is reached, the percolation of solid phase seems to occur and UPV starts to increase. In this period, more and more hydration products continues to be intersected, and consequently the stiffness or E-modulus of material increases rapidly. After that stage, UPV increases only slightly since high hydration degree was already reached and further hydration becomes minimal. The UPV evolution of mixes with different fibre contents is very similar to that of the ones without fibres addition, just a slightly postpone on the microstructure formation process when comparing with the UPV curve of the mixes without fibres addition was observed, which is in accordance with temperature evolution under semi-adiabatic conditions (Figure 4-a). As can be observed in Figure 4-a, after 3h, temperature evolution is characterized by a strong heat release, which lasted for about 6 h. It was also noted that the temperature development peak at the period of maximum activity reached 42ºC, with an average room temperature of 25ºC. The UPV suffer a decrease at approximately 9h (after achieved the peak and hydration process started slow down) wich can be related with the orientation of the fibers, since it can affect the UPV. Previous study proved that for the same sample, the UPV was higher along the direction where more fibers were oriented [20].

The evolution of E-modulus identified according to EMM ARM methodology has already been established by several previous studies [21], [22], [23], [24]. The resonant frequencies identified by the EMM-ARM method for the three studied cement composites mixtures covered a wide range of frequencies, from ~ 60 Hz to 200 Hz within the testing period. Young Modulus evolution curves, which are present in Figure 5, appear to be plausible, showing an initial dormant period, where the it remains almost constant. After this threshold, close to 3 h, the E-modulus evolved significantly for all tested specimens until approximately 9 hours of curing period, after which a dramatic reduction in the slope of Young Modulus evolution occurs. This is in accordance with previous methodologies findings. Concerning UHPFRC specimens, similar evolution kinetics was obtained, and after 7 days a Young modulus between 30-34 GPa was achieved. The addition of fibres in UHPFRC did not significantly influence its elastic modulus, which corroborates with others studies [5], [16], [23], [25], [26].

4. CONCLUSIONS

In the current study, the reliability of NDT methods for the evaluation of stiffness-related properties of UHPFRC has been investigated. Based on the findings of this investigation, the following conclusions have been drawn:

- Based on the EMM ARM testing method, the addition of fibres did not present significant influence on stiffness. Indeed, the Young modulus of UHPFRC with 3.0% steel fibres is slightly higher (almost 5%) compared to the respective values obtained for UHPFRC without steel fibres.
- From the correlation of different methodologies, similar kinetics during all period of test were observed. At least three stages could be identified. A first dormant stage, where specimens behaves closer to a fluid, up to 3h maximum, then, when solid structure starts to form and more hydration products are available, UPV and Young Modulus starts to increase rapidly. Finally, a lower-rate increase stage started which corresponds to the point when a high hydration degree was already reached and further hydration becomes minimal.
- NDT seems to be promising methodologies for assessing early age evolution of UHPFRC kinetics, having advantages such as easy application and low-cost.

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