COMBINED NON-DESTRUCTIVE METHOD FOR EVALUATING THE MECHANICAL PERFORMANCE OF ULTRA HIGH PERFORMANCE FIBRE REINFORCED CONCRETE (UHPFRC)

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ABSTRACT

Non Destructive Testing (NDT) of concrete is extensively used for the in-situ assessment of the mechanical characteristics of concrete. The main advantage of NDT techniques is that they are simple and quick, while the mechanical characteristics of concrete can be evaluated without causing any damage in the existing structures. However, the characteristics of various concrete types are highly affected each time by their mix composition. Hence, the reliability of NDT techniques is questionable and appropriate validation and calibration is required.

In the current study, two different mixes have been examined, one representing Ultra High Performance Concrete (UHPC) without steel fibres, and another one with 3% steel fibres representing Ultra High Performance Fibre Reinforced Concrete (UHPFRC). Compressive tests have been conducted alongside with Ultrasonic Pulse Velocity (UPV) and Rebound Hammer (RH) measurements. The experimental results have been used for the development of a model for the evaluation of the mechanical characteristics of UHPFRC using the combined UPV and RH method (SonReb). The results of the current study highlight the efficiency and the reliability of SonReb method for the estimation of the compressive strength of UHPC and UHPFRC using RH and UPV results.

Keywords: UHPFRC, NDT, Rebound Hammer, Ultrasonic, SonReb,

1. Introduction

UHPFRC is a novel material with superior strength and energy absorption (Graybeal, 2006). Mechanical properties of this material have been extensively investigated in previous studies (Kang *et al.*, 2010; Yoo *et al.*, 2013; Kang & Kim, 2011; Hassan, Jones, and Mahmud, 2012; Toledo *et al.*, 2012). UHPFRC composition differs from that of an ordinary concrete as it contains high amount of silica fume, steel fibres and no coarse aggregates. The percentage of the steel fibres is one of the most crucial parameters affecting the flexural strength and the ductility of UHPFRC elements. According to previously published studies (Kang *et al.*, 2010; Kang & Kim, 2011; Hassan *et al.*, 2012; Toledo *et al.*, 2012; Yoo *et al.*, 2013; Lampropoulos *et al.* 2016), increment of steel fibres amount results to an increment of the flexural strength, while the ductility is also reduced.

In literature (Graybeal, 2006; Ahlborn, Peuse, and Misson, 2008; Graybeal, 2005; BFUP AFGC, 2002; Shah & Ribakov, 2011), there are several investigations on the mechanical properties of UHPFRC based on conventional destructive methods. However there are very limited studies on the evaluation of the mechanical properties of UHPFRC using NDT (Washer *et al.*, 2004; Hassan & Jones, 2012). Washer *et al.* (2004) investigated the applicability of UPV on UHPFRC, and the effect of steel fibres content on the wave velocity was examined. The effectiveness of UPV was also examined by Hassan and Jones (2012) and the need for further investigation was highlighted.

There are several NDT methods and two of the most commonly used for in-situ applications are the RH and the UPV techniques. For ordinary concrete, RH test is a quick method for determining the quality of concrete based on its surface hardness, and there are proposed models for the correlation of the rebound hammer index values with the compressive strength. UPV method is based on measurements of the velocity of an ultrasonic pulse which is generated by an electro-acoustical transducer through concrete. Based on the velocity measurements, the structure of concrete alongside with its density and any cracks or defects can be evaluated. In the last few years, combination of more than one methods has become more popular in order to improve reliability and reduce the effect of errors induced during the application of individual methods (Concu *et al.*, 2011 and Breysse, 2012). SonReb is a method which is based on the combination of RH and UPV tests results; in order to develop reliable models for the estimation of the compressive strength of concrete.

Until now, there are not any published studies on combined NDT methods for UHPC and the main aim of this paper is to investigate the effectiveness of combined NDT method for the estimation of the compressive strength of UHPFC and UHPFRC. Two different mixes have been examined, with and without steel fibres (UHPFRC and UHPC), and compressive tests have been conducted alongside with RH and UPV tests at different ages. These results have been used for further analysis and for the development of SonReb models.

2. Experimental procedure

2.1 Preparation of UHPFRC and testing

In the current study two different mixes have been examined, one with 3% steel fibres (UHPFRC) and another one without steel fibres (UHPC). UHPFRC mix design is presented in Table 1, and this is based on a previous study (Hassan *et al.* 2012). UHPC mix design is the same with the mix design presented in Table 1, with the only difference that steel fibres have not been added to this mix.

Table 1. Mix design of UHPFRC

Material	Mix proportions (kg/m^3)
Cement	657
GGBS	418
Silica fume	119
Silica Sand	1051
Superplasticizers	59
Water	185
Steel fibers (3%)	235.5

For the preparation of the mix, silica sand with maximum particle size of 500μm has been mixed together with dry silica fume with retention on 45 μm sieve < 1.5 %, Ground Granulated Blast Furnace Slag (GGBS), and cement class 32.5 R type II. Micro silica with fine particles has also been used in order to increase the density of the matrix and to improve the rheological properties of the mix. Low water over cement ratio has been used together with polycarboxylate superplasticizer. Steel fibers with 13mm length, diameter 0.16mm, tensile strength 3000 MPa, and modulus of elasticity equal to 200 GPa have been used for the UHPFRC.

Regarding the mixing procedure, all the dry ingredients are mixed first. Then, water and superplasticizer are added to the mix and steel fibers are added gradually at the end through sieving. Cubic specimens with dimension 100mm have been cast and cured under normal room conditions (relative humidity 42% and temperature 20 C), and compressive alongside with nondestructive tests have been conducted at 1, 3, 7 and 28 days after casting.

NDT have been conducted using Schmidt Hammer (Fig. 1a) and Ultrasonic testing instrument (Fig. 1b) while at the end of the NDT, while compressive tests have also been conducted. Three specimens have been examined for each mix for all the examined ages.

(a)

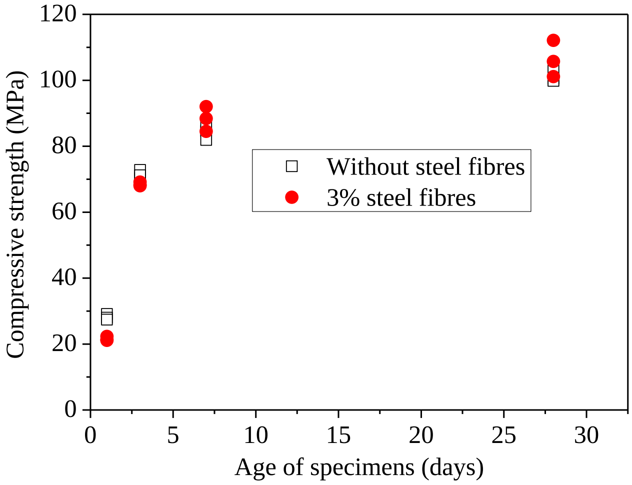
(b)

Fig. 1. Non-destructive testing using **a)** Schmidt Hammer and **b)** Ultrasonic testing instrument

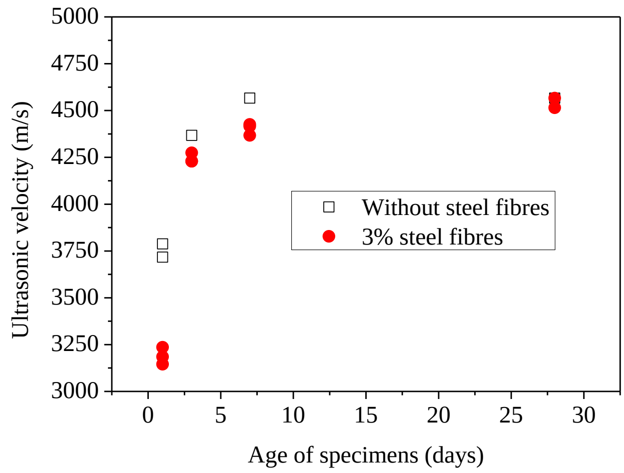
From RH tests the square of the coefficient of restitution values (Q-values) have been recorded, while from UPV the pulse velocity has been recorded for all the examined specimens. These results have been used to correlate NDT characteristics to the respective compressive strength values.

2.2 Experimental results

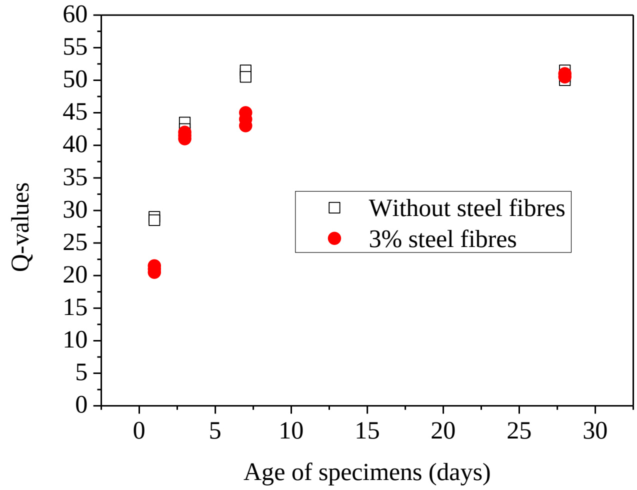
All the individual results for the development of compressive strength, ultrasonic velocity and Q-values with the age of the specimens for the mixes with and without steel fibres, are presented in Fig. 2a, 2b and 2c respectively.



(a)



(b)

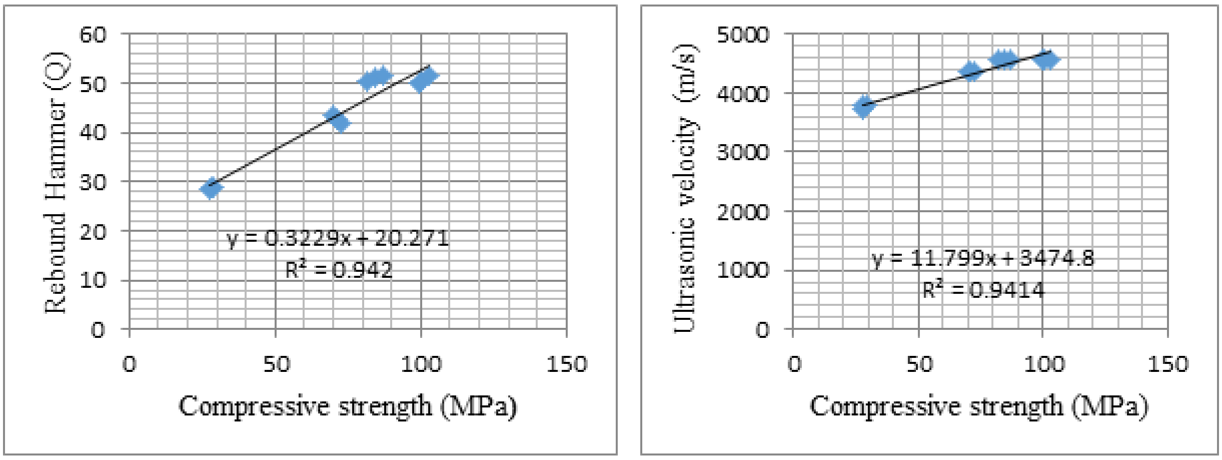


(c)

Fig. 2. **a)** Compressive strength, **b)** ultrasonic velocity, and **c)** rebound hammer index values for specimens with and without steel fibres at various ages

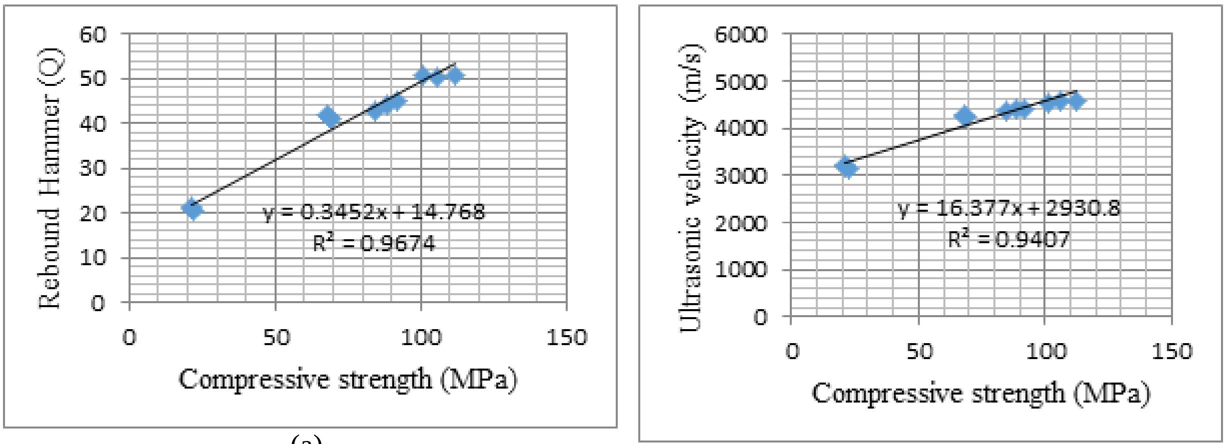
The results of Fig. 2a indicate that, as expected, the addition of 3% of steel fibres leads to an increment of almost 5% of the compressive strength values which is clear after 7 days of curing. The UPV results (Fig. 2b) indicate that the overall velocity of the ultrasonic is reduced when steel fibres are added to the mix, which could be attributed to the longer path lengths in case of specimens with steel fibres. This observation is in agreement with a previous study where the effect of steel fibres on the ultrasonic results was investigated (Washer *et al.* 2004). Regarding the square of the coefficient of restitution values (Q-values) (Fig. 2c), reduction of the values is shown by the addition of steel fibres at the age of 1 and 7 days after casting.

Using the mean values of the results of Fig. 2 for the various ages, simple linear regression is adopted to correlate RH (Q-values) and UPV values with the compressive strength results, while coefficients of determination (R^2) have also been calculated for all the examined cases. The results for specimens with and without steel fibres are presented in Fig. 3 and Fig. 4 respectively.



(a) (b)

Fig. 3. Correlation of compressive strength with **a)** RH (Q-values) and **b)** UPV results and respective regression lines for UHPC (without steel fibres)



(a) (b)

Fig. 4. Correlation of compressive strength with **a)** RH (Q-values) and **b)** UPV results and respective regression lines for UHPFRC (with 3% steel fibres)

The results of Fig. 3 and Fig. 4 indicate that high coefficients of determination (R^2) have been obtained (above 0.94) for the regression lines for both RH and UPV results. The highest R^2 value (0.9674), has been obtained for Q values versus compressive strength distribution for UHPFRC with 3% steel fibres (Fig. 4a).

2.2 SonReb method

All the experimental results presented in the previous section (Q-values, ultrasonic velocity, and compressive test results) have been used to determine SonReb curve coefficients for both mixes with and without steel fibres (UHPFRC and UHPC). Eq. 1 is the general equation which relates compressive strength to UPV values and to RH (Q-values) results.

$$f_{ck} = a \cdot V^b \cdot S^c \tag{1}$$

where:

V:	is the ultrasonic pulse velocity,
S:	is the Q-value from the rebound hammer tests,
a, b, c	are coefficients depended on the material.

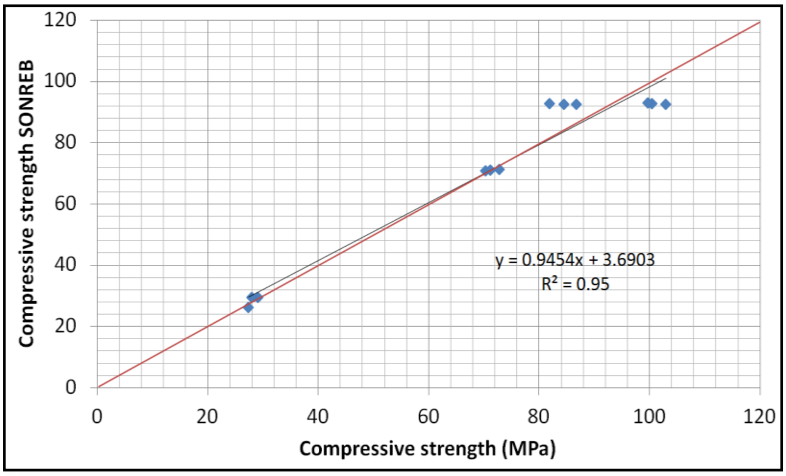
The natural logarithms of the data of Fig. 2 have been initially calculated, and then 'LINEST' function in Microsoft Excel has been used to calculate straight lines to best fit the data using the 'least squares'.

Based on these analyses, the following values for coefficients a, b, c for UHPC and UHPFRC with 3% steel fibres have been determined.

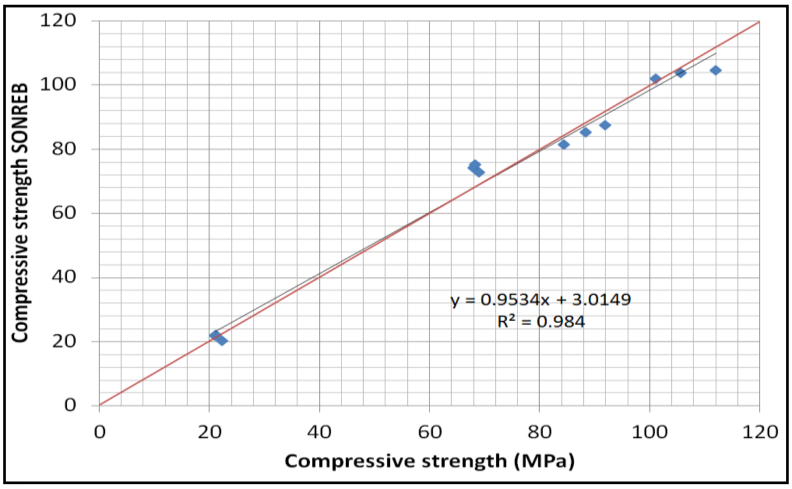
Table 2. SonReb coefficients

Coefficient	Values calculated for plain UHPC	Values calculated for UHPFRC with 3% steel fibres
a	9.94E-23	1.61E-08
b	6.626349	2.275342
c	-0.1642	0.87

The values of Table 2 have been used to calculate compressive strength values using SonReb (Eq. 1) and these values are correlated to the actual compressive strength values obtained from the mechanical tests (Fig. 5). Linear regression has been adopted to correlate these values and coefficients of determination (R^2) have been calculated (Fig. 5).



(a)



(b)

Fig. 5. Correlation between compressive strength values calculated using SonReb method and actual compressive strength values for **a)** UHPC (without steel fibres) and **b)** UHPFRC (with 3% steel fibres)

The results of Fig. 5 indicate high coefficients of determination (R^2) for the regression lines for both UHPC and UHPFRC. Slightly higher coefficient of determination (R^2=0.984) has been obtained for UHPFRC specimens with 3% steel fibres compared to the respective values for UHPC without steel fibres (R^2=0.95). Also from the results of Fig.5 it is evident that SonReb method can be used to accurately evaluate the compressive strength of UHPC and UHPFRC, since in both cases the linear regression models are very close to the diagonal lines of the graphs.

Conclusions

In the current study the reliability of NDT methods for the evaluation of the compressive strength of UHPC and UHPFRC has been investigated. Ultrasonic Pulse Velocity (UPV) and Rebound Hammer (RH) tests have been conducted at various ages alongside with compressive tests. These results have been used to develop models for the correlation of NDT results with mechanical testing results while combined SonReb method has also been examined. Based on the findings of this investigation, the following conclusions have been drawn.

Effect of steel fibres:

- As expected, the addition of 3% of steel fibres leads to a slight increment (5%) of the compressive strength values. The addition of steel fibres leads to an overall reduction of the RH (Q-values) and UPV values.

NDT versus compressive strength results:

- Regarding the correlation of RH and UPC results with compressive strength values, it has been observed that high coefficients of determination were obtained for linear regression models.
- SonReb method has also been examined, where RH, UPV and compressive test results were used to develop reliable models for the evaluation of compressive strength of UHPC and UHPFRC. Based on these results, it has been found that SonReb method can offer high degree of accuracy and is highly recommended for the prediction of the compressive strength of UHPC and UHPFRC.

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