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Combined Non-Destructive Testing (NDT) method for the evaluation of the mechanical characteristics of Ultra High Performance Fibre Reinforced Concrete (UHPFRC)

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HIGHLIGHTS

- SonReb models have been found to be the most accurate for both f_c and E_{cm}.
- In all the examined SonReb results for f_c and E_{cm}, error below 10% has been achieved.
- SonReb parameters need to be calibrated to take into account variations in mixtures' composition.

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ABSTRACT

Ultra-High Performance Fibre Reinforced Concrete is a material which is becoming increasingly popular in structural applications, mainly due to its superior mechanical characteristics. The mechanical properties of this material are of high importance and the development of non-destructive techniques is vital for the evaluation of the mechanical characteristics of existing structures. In the current study, Ultra-High Performance Fibre Reinforced Concrete with different amounts of steel fibres has been examined. Compressive and tensile tests have been conducted alongside with Ultrasonic Pulse Velocity and Rebound Hammer measurements and the development of appropriate empirical non-destructive models has been examined.

1. Introduction

Ultra High Performance Fibre Reinforced Concrete (UHPFRC) is a novel material with superior strength and energy absorption [1]. UHPFRC composition differs to that of an ordinary concrete as it contains low water over cement ratio, silica fume, steel fibres and silica sand. Steel fibres content is one of the most crucial parameters of the mix and important mechanical characteristics such as the tensile strength, the flexural strength and the ductility of UHPFRC elements are highly affected by the percentage of steel fibres. According to previously published studies [2–7], increment of steel fibres amount results to an increment of the flexural strength. In literature [1,8–11], 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 Non-Destructive Testing (NDT) [12,13] and there are not any published studies to date on combined NDT methods for the estimation of the mechanical characteristics of UHPFRC. Washer et al. [12] investigated the applicability of Ultrasonic Pulse Velocity (UPV) on UHPFRC, and the effect of steel fibres content on the wave velocity. The effectiveness of UPV was also examined by Hassan and Jones [13] and the need for further investigation was highlighted.

NDT methods are useful for the evaluation of the condition of structures, by performing indirect assessment of concrete properties. NDT has many advantages as structural damage during testing is reduced, is relatively simple and less time consuming, and there is possibility of taking measurements even from structures where cores cannot be drilled [14,15]. NDT methods have also been proposed for the assessment of the damage and for the survey of detailed condition of concrete structures and road pavements [16]. There are several NDT methods and two of the most commonly used for in-situ applications are the Rebound Hammer (RH) and the UPV techniques. RH test is a quick method for

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determining the quality of concrete based on its surface hardness [17]. Schmidt Rebound Hammer is used to measure the hardness of the surface. Schmidt hammer consists of a mass and a spring which is sliding along a bar which impacts on the end of a steel plunger. After the impact on the concrete surface, the mass rebounds from the steel plunger and moves an index rider. Schmidt hammers normally measure either R-value or Q-value. R-value is the rebound index which is being calculated by the ratio of paths of the mass before and after impact. Q-value or coefficient of restitution is the ratio of kinetic energies of the mass before and after the impact. The energy absorbed by the concrete depends on the stress-strain characteristics of concrete and hence on the modulus of Elasticity and the maximum compressive strength. UPV method [18,19] is based on measurements of the velocity of an ultrasonic pulse which is generated by an electro-acoustical transducer through concrete. Using UPV results, the structure of concrete alongside with its density and any cracks or defects can be evaluated. In the literature, there are various proposed models for conventional concrete for the correlation of RH index values and UPV with concrete compressive strength and modulus of Elasticity [20–39]. In the last few years, combination of more than one method is becoming more popular since they can offer improved reliability and limited errors compared to respective results of individual methods [21,40–44]. SonReb method is one of them. The term SonReb is created by combing the terms 'Sonic' and 'Rebound' and is a method which is based on the combination of UPV and RH tests results; and until now has only been used for the development of models appropriate for the prediction of conventional concrete compressive strength. This combined method is more accurate than the single NDT methods as takes into consideration two parameters (UPV and RH) which are influenced in different ways by similar factors related to concrete density and hardness. The SonReb method is an empirical method to determine appropriate models for the correlation of the mechanical characteristics (normally compressive strength) with the UPV and RH index values. By using multiple-regression analysis, the mechanical characteristics of the examined material is expressed as a function of the average RH and UPV values and there are published models in the literature for the estimation of the compressive strength of conventional concrete [45–48].

To date there are very limited studies on the use of NDT techniques for the evaluation of the mechanical performance of UHPFRC [12,13] and there are not any published studies on combined NDT methods (i.e. SonReb). The main aim of this study is to evaluate the reliability of NDT methods for the assessment of the mechanical characteristics (compressive strength and modulus of Elasticity) of UHPC and UHPFRC. Various mixes have been examined, with and without steel fibres (UHPFRC and UHPC), and compressive and tensile tests have been conducted alongside with RH and UPV tests at different ages. The application of established relationships for the correlation of the dynamic modulus of Elasticity with the UPV for homogeneous isotropic elastic medium have been examined [12,13] and the results have been compared to the experimental values. The experimental results have been used for the development of NDT models using UPV, RH and combination of UPV and RH values (SonReb).

2. Experimental procedure

2.1. Preparation of UHPFRC

In the current study, three different mixes have been examined; one using 1% steel fibres (UHPFRC-1), one using 3% steel fibres (UHPFRC-3) and another one without steel fibres (UHPC). UHPFRC mix design is based on previous studies [5,7] where 2% and 3% (by volume of the mix) steel fibres have been used. In the current study, the selection of the three mix designs of Table 1 (0%, 1% and 3% steel fibres) has been made in order to evaluate the effect of the steel fibres quantity by comparing the results of mixes without steel fibres (UHPC), with low (UHPFRC-1) and with relatively high percentage of steel fibres (UHPFRC-3). All three concrete mix designs are presented in Table 1.

Silica fume, silica sand, Ground Granulated Blast Furnace Slag (GGBS), and cement class 32.5 R type II have been used together with polycarboxylate superplasticizer. Steel fibres with 13 mm length, diameter 0.16 mm, tensile strength 3000 MPa, and modulus of Elasticity equal to 200 GPa have also been incorporated in the UHPFRC mixes.

Regarding the mixing method, high-shear pan mixer (Zyklos ZZ 75 HE) has been used for all the examined mixes. Dry ingredients have been mixed first, and then superplasticizer has been added in the mix followed by the gradual addition of steel fibres through sieving. All specimens have been placed in a water curing tank until the testing day.

Cubic specimens with dimension 100 mm have been tested under compression alongside with nondestructive tests (RH and UPV) at 1, 2 (for UHPFRC-1 only), 3, 7, 14 (for UHPFRC-1 only), and 28 days after casting. For the evaluation of the modulus of Elasticity and the tensile strength, dog-bone specimens have been cast and tested at 1, 2 (for UHPFRC-1 only), 3, 7, and 28 days. These testing ages have been selected in order to obtain a wide range of experimental results which will be able to be used for the regression analyses and for the development of empirical models. Three specimens have been tested for each mix and for all the examined ages. Geometry of dog-bone specimens is illustrated in Fig. 1a and cube and dog-bone samples after casting are presented in Fig. 1b.

2.2. Mechanical and Non-Destructive Testing

The compressive strength tests have been carried out using an Avery Denison compressive testing machine and the tests have been conducted in accordance with BS EN 12390-3:2009 [49] with a loading rate of 0.6 MPa/s (Fig. 2a). For the tensile testing of the dog-bone shaped specimens, tests under displacement rate of 0.007 mm/s have been conducted using an Instron universal testing machine. Linear Variable Differential Transformer (LVDT) and the special setup which is presented in Fig. 2b have been used in order to measure the average of the extensions of the two sides of the specimens [8]. The accuracy of the strain measurements has been validated using Digital Image Correlation (DIC) system and these values together with the load recordings have been used for the evaluation of the modulus of Elasticity values.

For the Rebound Hammer testing, nine impacts have been conducted at each specimen and the median value has been calculated as proposed by IS 13311 [18] and BS EN 12504-2 [50]. SilverSchmidt concrete Rebound Hammer has been used in the current study. Tests have been conducted on the moulded surfaces and all readings have been taken at a distance not nearer on edge than

Table 1
Mix design of UHPFRC.

Material	Mix proportions (kg/m^3)		
	UHPC	UHPFRC-1	UHPFRC-3
Cement	657	657	657
GGBS	418	418	418
Silica fume	119	119	119
Silica Sand	1051	1051	1051
Superplasticizers	59	59	59
Water	185	185	185
Steel fibres	0	75.2	235.5