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Effect of Coupling Media on Ultrasonic Pulse Velocity in Concrete: A Preliminary Investigation

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Abstract**—**Measurement of the ultrasonic pulse velocity (UPV) is an important tool in diagnostic examination of concrete. In this method piezoelectric transducers are normally held in direct contact with the concrete surface. The current study aims to test the hypothesis that a preferential coupling effect might exist i.e. that the speed of sound measured depends on the couplant used. In this study, different coupling media of varying acoustic impedance were placed between the transducers and concrete samples made with constant aggregate content but with different compressive strengths.

The preliminary results show that using coupling materials (both solid and a range of liquid substances) has an effect on the pulse velocity measured in a given concrete. The effect varies depending on the material used. The UPV measurements with solid coupling were higher than these from the liquid coupling at all strength levels. The tests using couplants generally recorded lower UPV values than the conventional test, except when carbon fiber composite was used, which retuned higher values. Analysis of variances (ANOVA) was performed to confirm that there are statistically significant differences between the measurements recorded using a conventional system and a coupled system.

Keywords—Compressive strength, coupling effect, statistical analysis, ultrasonic.

I. INTRODUCTION

THE ultrasonic pulse velocity method is one of the oldest and most widely used non-destructive tests for concrete, since it is easy to perform, quick and inexpensive [1]. It has been used for assessing concrete strength, investigating the homogeneity of concrete, studying the durability of concrete, and measuring the depth of surface cracks in concrete. This method is based on the principle that pulse velocity of ultrasound waves propagating through a solid material depends on the density and the elastic properties of that material.

A great deal of research has been undertaken to investigate the influence of concrete properties on the pulse velocity of ultrasound waves. Ohdaira and Masuzawa [2] studied the effect of degree of water saturation on pulse velocity measurement in concrete. They found that changes in the pulse velocity and the transmission of high frequency component were nearly proportional to the variation of the degree of saturation in concrete. Lin, Lai [3] investigated the influence of mix proportion on the pulse velocity. They found that changing the fine aggregate to total aggregate ratio had comparatively little impact on the ultrasound pulse velocity of the concrete over a range of water to cement ratios. The ultrasonic pulse velocity was inversely proportional to the cement paste volume, especially for concrete mixes with high water to cement ratios. They also proposed a mathematical model for the prediction of concrete pulse velocity. Abo-Qudais [4] investigated the effects of water to cement ratio, curing time, and aggregate gradation on the measured pulse velocity. It was noted that the aggregate gradation and water to cement ratio had a significant effect on the pulse velocity, while the effect of curing time was just limited to the first 7 days after curing. Lin, Kuo [5] researched the relationship between the ultrasonic pulse velocity and the concrete compressive strength. They proposed five simulated curves for this relationship, where the coarse aggregate content was considered the dominant factor. Trtnik, Kavcic [6] illustrated the efficiency of using artificial neural networks instead of the traditional static modelling in establishing reliable compressive strength and ultrasonic pulse velocity relationships. Results indicated that the artificial neural network had a great potential to produce flexible numerical methods for the compressive strength estimation of the concrete by using the ultrasonic pulse velocity data and some of mix parameters of concrete.

Few studies have investigated the effect of coupling on pulse velocity measurement. Purnell, Gan [7] investigated the potential for using air-coupled (i.e. non-contact) ultrasonic equipment compared to traditional ultrasonic equipment (PUNDIT). The preliminary results showed that the air-coupled ultrasonic equipment could be used as a non-destructive method for testing concrete of thickness up to 75 mm. A strong correlation between the pulse velocity and the compressive strength was observed in both systems. However, the slope of the curve was much steeper in the air-coupled test than the PUNDIT test. The PUNDIT tests gave much higher values of pulse velocity for concrete mixes of normal compressive strength (i.e. <50 MPa) than the air-coupled tests. The researchers hypothesised that this discrepancy was due to the effect of preferential coupling between the ultrasound wave and the constitute materials of concrete.

Berriman, Purnell [8] investigated the influence of aggregate content and storage humidity on the pulse velocity of ultrasound in concrete again using air-coupled ultrasonic equipment compared to a PUNDIT contact system. They found that there was a strong positive linear correlation between the aggregate content and the pulse velocity. A positive correlation between the storage humidity and the pulse velocity was also observed, and a correction factor for humidity deduced. However, the contact system once again

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consistently gave high values for the pulse velocity and also displayed a stronger dependence on the aggregate content than the non-contact system. The researchers again attributed this discrepancy preferential coupling between the ultrasound wave and the constituent materials of concrete, in essence suggesting the PUNDIT measurements may have been dominated by the properties of the aggregate rather than those of the cement paste; yet it is the properties of the paste that dominate the properties of the concrete. Other investigators have investigated air coupling without comparison to contact methods. Cetrangolo and Popovics [9] developed a contact-less (air-coupled) ultrasonic test setup for scanning embedded flaws in concrete by using modified piezoelectric transducers and digital signal processing. Balsa wood was added to traditional ultrasonic transducers of 54 kHz central frequency as a matching layer between the transducer crystal and the air. Time averaging technique and continuous wavelet transform analysis were used for processing the signals. A proposed algorithm was then applied for automatic detecting of the interior defects in concrete. A (400×400×100) mm concrete sample was cast for this work before casting fabricated inclusions that were added to the mould for defects stimulation. The results showed that the locations of the inclusions were identified successfully according to the two dimensional image of air- coupled ultrasonic scanning.

In summary, although air-coupling techniques have shown positive practical results [10], no literature has been published to-date further examining the discrepancy in pulse velocity measurements attributed to coupling effects by experimenting with different coupling media. The main aim of this research is to investigate the hypothesis that a preferential coupling effect could occur between the ultrasound wave and the constituent materials of the concrete. In this work different coupling media of varying acoustic impedance will be used to replicate the effect.

II. EXPERIMENTAL PROGRAMME

A. Coupling Materials

TABLE I
DETAILS OF THE COUPLING MATERIALS OBTAINED FROM REFERENCE [11]

Materials	Material Status	Longitudinal pulse velocity m/sec	Density kg/m^3	Acoustic Impedance Kg/m^2.s
concrete	solid	(4430-4960)	(2300-2460)	(6-9) ×10^6
Rubber (Neoprene)	solid	1600	1310	2.10×10^6
Perspex (Poly-methacrylate)	solid	2750	1190	3.26×10^6
Carbon fiber composite	solid	4260	1470	6.26×10^6
Water	liquid	1480	1000	1.48×10^6
Propanol (n-polyalcohol)	liquid	1220	804	0.98×10^6
Vegetable Oil (Sunflower)	liquid	1450	920	1.34×10^6

Various solids and liquids were chosen based on availability, practical suitability for use as a couplant, and to cover a range of varying acoustic impedance. The coupling materials with their details are shown in Table I.

B. Concrete Mixes

Five concrete mixes with target 28-day mean compressive cube strength of 25, 40, 60, 80 and 100 MPa were cast using Portland cement, sand and a constant coarse aggregate content of 20mm. The details of the mixes are given in Table II.

TABLE II
MIXTURE PROPORTION OF CONCRETE

Mix designation	Target 28-day mean compressive strength MPa	Mixture Proportion kg/m^3				
		Cement	Water	Super-plasticizer	Fine Aggregate	Coarse Aggregate
M1	25	290	170	-	742	935
M2	40	405	195	-	830	935
M3	60	550	215	-	695	935
M4	80	550	143	5.5	695	935
M5	100	550	138	11	695	935

C. Ultrasound Pulse Velocity Test

The UPV was measured using a new commercial testing device PUNDIT Lab$^+$, manufactured by Proceq Switzerland. The device (pulse generator) coupled to pair of transducers with a central frequency of 54 kHz. Direct transmission configuration was used through this work, the transducers were held at opposite sides of the concrete sample. By measuring the time taken by the pulse to be transmitted and received over a known path length, the velocity of the pulse can be computed from the relationship:

$$V = d/t$$

The test was performed at age of 7, 28 and 90 days on prisms of 100×100×500 mm, and for each mix three samples were tested at each age. For the conventional test a very thin layer of gel couplant was applied between the transducers and the test sample as is normal practice on-site. A frame was used to consistently hold and align the transducers with the sample as shown in Fig. 1. For the solid coupling slices of the solid material with dimension of 100×100 mm of varying thickness (as shown in Fig. 2) was placed between the transducers and the sample. Liquid coupling tests were performed by using a plastic tube. The transducer was inserted with one end and the other end placed on the sample surface and sealed with silicon as shown in Fig. 3. Then the tube was filled by injecting the liquid through a hole on its surface. Each sample was removed from the curing room and placed to dry at room temperature for 30 minutes before taking measurements. Ten readings per sample were taken at each test. Corrections were applied to the coupled test, as the recorded time is the transit time within the concrete sample and the coupling material. Before starting the coupled test, the transit time within the coupling material was recorded. Thus the transit time through concrete can be calculated using the following relationship:

$$t_{concrete} = t_{total} - t_{coupling\ material}$$

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D. Compressive Strength Test

The compressive strength test was carried out on 100mm cubes at the age of 7, 28 and 90 days. For each mix, a set of three cubes was tested at each age by using the Servocon system digital machine.

III. RESULTS AND DISCUSSION

The pulse velocity of ultrasound wave through concrete obtained by the use of the conventional system (i.e. with the transducers in direct contact with the concrete surface via a nominal layer of couplant) and by placing finite thicknesses of different coupling media between the transducers and the concrete surface are plotted with compressive strength in Fig. 4.

Using solid rubber or Perspex couplant returns lower values for the pulse velocity according to that of the conventional test for mixes with compressive strength (≤ 60 MPa) but return approximately similar values for mixes with higher compressive strength. This behavior has been seen in previous air coupling tests [7]. Using carbon fiber couplant returns higher values for the measurements of the pulse velocity than for that of the conventional test at all compressive strength levels.

All three liquid couplant tests (oil, propanol or water) returned much lower values for the pulse velocity compared to the conventional test and the solid coupling materials at all compressive strength levels.

Also, it can be seen that the relationship between the pulse velocity, c, and the compressive strength, S, of the conventional test was approximately linear with $\Delta c/\Delta S$ of about 4 m/Mpa.sec. Most of both the solids and liquids coupling tests returned similar values for $\Delta c/\Delta S$; i.e., the c/S lines are simply “shifted vertically” with respect to that of the conventional test. However, the carbon fiber and Perspex relationships showed a noticeable difference with $\Delta c/\Delta S$ values of approximately 9 and 7 m/Mpa.sec respectively. Both these behaviors are rather different to that of previously reported air coupling tests [7], where the slope of the c/S curve was much steeper in the air-coupled test than the conventional test (PUNDIT test) with a $\Delta c/\Delta S$ value of approximately 45 m/Mpa.sec. However, the concrete mixes that were used in the air coupling work had a different water to cement ratios and coarse aggregate contents. In this work, mixes with different water to cement ratios and a constant coarse aggregate content were used.

Based on the preliminary results, it can be noted that the uncoupled and coupled systems are returning different values for the pulse velocity of the concrete. It is clear that the measured speed of sound depends on the couplant used. Concrete is a multiphase material, where the speed of sound in aggregate is generally higher than that through cement paste, and the two phases will have slightly different acoustic impedance. It is thus reasonable to assume that the differences are due to preferential coupling effects.

Fig. 1 Ultrasonic pulse velocity test instrument with concrete specimen in position

Fig. 2 Testing the concrete specimen with solid coupling

Fig. 3 Testing the concrete specimen with liquid coupling

The highest speed of sound was measured using the couplant with closest match of acoustic impedance with concrete (carbon fibre). All other couplants had lower acoustic impedance than the concrete. As a matter of fact, the amount of energy transmitted through an interface depends on acoustic impedances of the two media. If the two media have close impedance values, more energy will be transmitted. As the solid materials have acoustic impedance higher than those of liquids compared to concrete’s impedance, thus it is thought that the more energy will be transmitted through the interface solid-concrete. There seems to be relationship between the speed of sound measured and the difference between the acoustic impedance of the couplant and the concrete. The steel transducer (i.e. non coupled system) has a very high acoustic impedance(>40), but it not clear why this should give a lower speed of sound than the carbon fibre yet a higher speed of sound than the liquid couplants-more research is required as the relationship is clearly complex.

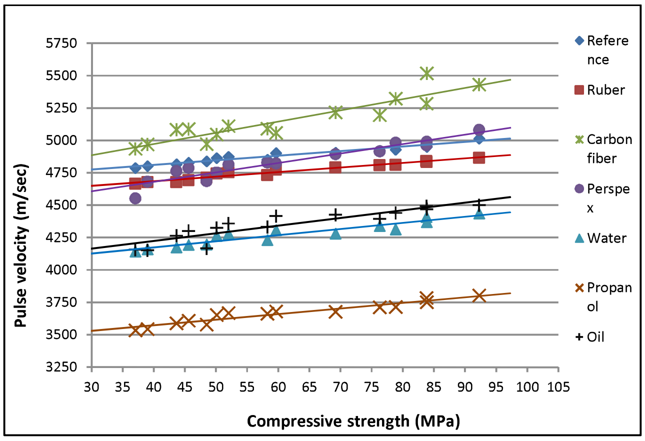

Fig. 4 Pulse velocity vs compressive strength: solid coupling, liquid coupling and conventional test

IV. STATISTICAL ANALYSIS

One-way analysis of variance (ANOVA) was conducted on the coupled and uncoupled UPV measurements to determine if there are statistically significant differences between both systems [12]. The mean, standard deviation and normality test are shown in Table III. The details of ANOVA test are given in Table IV. As the ANOVA test was statistically significant, a post hoc test (Games-Howell) was used to test all possible combinations of pairwise comparison between the coupling material tests and with the conventional test. The results of the multiple comparisons are presented in Table V. The difference between measurements of Perspex test and conventional test was statistically not significant and with rubber test as well. Also, there is no statistical significance for the difference between measurements of water and oil tests. However, all differences of the other comparisons were statistically significant.

TABLE III
SECOND MOMENT STATISTICS AND NORMALITY TEST

Test	Statistics		Shapiro-Wilk test		
	Mean	Standard deviation	Test Statistic	P value	Data distribution
Conventional	4885	66.75	0.971	0.875	normal
Rubber coupling	4760	65.17	0.946	0.467	normal
Perspex coupling	4815	148.06	0.989	0.999	normal
Carbon fiber coupling	5117	131.44	0.949	0.504	normal
Water coupling	4274	90.80	0.962	0.725	normal
Propanol coupling	3664	81.76	0.965	0.781	normal
Oil coupling	4336	107.06	0.963	0.747	normal

TABLE IV
ANOVA TEST

ANOVA Statistic	df1	df2	P-value	Test Result
435.410	6	43.213	0.000	significant

TABLE V
GAMES HOWELL MULTIPLE COMPARISONS

(I) Coupling Material	(J) Coupling Material	Mean Difference (I-J)	P-value	Comparison Results
ConventionaL	Rubber	125*	0.000	different
	Water	611*	0.000	different
	Propanol	1220*	0.000	different
	Carbon Fiber	-232. *	0.000	different
	Perspex	70.	0.646	not different
	Oil	549*	0.000	different
Rubber	Conventional	-125 *	0.000	different
	Water	486*	0.000	different
	Propanol	1095*	0.000	different
	Carbon Fiber	-357*	.0000	different
	Perspex	-55	0.835	not different
	Oil	424*	0.000	different
Water	Conventional	-611*	0.000	different
	Rubber	-486*	0.000	different
	Propanol	609*	0.000	different
	Carbon Fiber	-843*	0.000	different
	Perspex	-541*	0.000	different
	Oil	-62	0.615	not different
Propanol	Conventional	-1220*	0.000	different
	Rubber	-1095*	0.000	different
	Water	-609*	0.000	different
	Carbon Fiber	-1452*	0.000	different
	Perspex	-1150*	0.000	different
	Oil	-671*	0.000	different
Carbon Fiber	Conventional	232 *	0.000	different
	Rubber	357*	0.000	different
	Water	843*	0.000	different
	Propanol	1452*	0.000	different
	Perspex	302 *	0.000	different
	Oil	781*	0.000	different
Perspex	Conventional	-70	0.646	not different
	Rubber	55	0.835	not different
	Water	541*	0.000	different
	Propanol	1150*	0.000	different
	Carbon Fiber	-302 *	0.000	different
	Oil	479*	0.000	different
Oil	Conventional	-549*	0.000	different
	Rubber	-424 *	0.000	different
	Water	62	0.615	not different
	Propanol	671*	0.000	different
	Carbon Fiber	-781*	0.000	different
	Perspex	-479 *	0.000	different

V. CONCLUSION

It has been shown that the coupling tests return different measurements for the pulse velocity of the concrete from that of the conventional test. It is thought that these differences due to a presentational coupling occur between the ultrasound wave and the constituent materials of the concrete. The measurements that recorded for the liquid coupling tests were lower than that of the solids coupling. All the coupling materials return lower values for the pulse velocity than that of the conventional test, except the carbon fiber. The relationship between the pulse velocity and the compressive strength was approximately linear for both the coupled and uncoupled systems, with similar slope but significant offset. However,

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the relationship of the carbon fiber and Perspex pulse velocity measurements with the compressive strength showed a noticeably different slope. It has also shown that the differences in pulse velocity measurements between the coupled system and the uncoupled system are statistically significant. This project is continuing to investigate the phenomena described here.

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