SIMULATION OF IN-SITU CONCRETE CONDITIONS USING A NOVEL ULTRASONIC TECHNIQUE

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Abstract: A novel ultrasonic technique is used to evaluate stresses within concrete structures by determining both second- and third-order elastic constants. A prism-shaped concrete sample is made identical to that of the structure and wave velocities are measured under various conditions. The special method used is based on a mode-conversion technique developed by the author and enables the accurate measurement of both compressional and shear waves using just one transducer.
The findings are compared with those made in-situ by applying pulse-echo and hammer-impact techniques. Initial results indicate that this method overcomes some of the difficulties related to testing concrete, namely the identification of echoes related to shear waves.

Introduction: Concrete is a multiphase material consisting of a coarse aggregate, a fine aggregate, sand and cement. The speed of sound in concrete depends on the relative concentration of the constituent particles, the degree of compaction, the moisture content and the nature and amount of defects present. Its coarse granular structure gives rise to a high degree of acoustic scattering and, hence, attenuation.

Concrete is used extensively for construction of defense and civilian structures. In defense applications, cement-based materials are often used as the primary structural components in facilities that are hardened against attack. Knowledge of the mechanical behavior of concrete during high-strain events is necessary in order to design structures capable of surviving attack.

In the civilian sector, concrete is used for a variety of construction applications, some of which may require very high performance characteristics. For example during an earthquake, which is typically composed of several different modes of shock wave with potentially very large associated strains [1].

In the laboratory, in-situ conditions of concrete can be simulated realistically on core samples extracted from a structure or moulded samples. Appropriate conditions of stress, fluid saturation, and temperature are imposed on the samples. Thus, reliable experimental data could be obtained and fed to predictive models that are used to assess the quality of both defense and civilian structures, which require materials characterization of not only the finished concrete, but its main constituents, namely, aggregate and mortar.

The presence of coarse aggregate requires that ultrasonic testing in concrete be conducted at relatively low frequencies in order to avoid excessive attenuation caused by scattering. In practice, the usual frequencies lie between 25 and 250 KHz, corresponding to wavelengths ranging from 160mm down to 16mm, depending on the nature of the sample. Ultrasonic techniques based on pulse-echo, pulse transmission, impact-echo and resonance methods have been widely used for the characterization of a variety of materials, including metals, ceramics and building materials [2,3].

The pulse through-transmission technique with the use of a goniometer is quite suitable for simulating in-situ conditions of concrete. The sample, in the form of a rectangular block, is mounted on a turntable which can be rotated in steps of 0.01° and located between a pair of heavily-damped compression wave probes, one transmitting and the other receiving. The complete arrangement is immersed in a water tank. Both compressional and shear waves could be generated within the sample depending on the angle of incidence [4,5].

Gregory et al described an interesting dual-mode ultrasonic apparatus with just one set of transducers for measuring elastic constants of rock samples [6]. The same configuration could be used for testing concrete samples. The dual-mode ultrasonic apparatus generates both waves and directs them alternately through a sample in a single mechanical assemblage. The transducer

assembly consists of two modified right-angle aluminum wedges placed in contact with the ends of a cylindrical solid sample. Wedge angles of 45° gave the most convenient geometry for guiding both compressional and shear waves through the sample in the desired manner.
In a more recent paper Marten et al developed a methodology with two sets of transducers for the determination of the elastic constants of porous, cementious materials as a function of applied hydrostatic pressures up to 1GPa [7]. The methodology can be performed upon bulk samples and in a fashion, which is more controlled than impact testing. Ultrasonic measurements were performed using high frequency 2.25MHz X-cut and Y-cut transducers for the generation and detection of compressional and shear acoustic modes respectively. Time of flight was measured in a through transmission configuration. When testing concrete in-situ, impact-echo and pulse transmission techniques are the most widely used [8].
The proposed method is based on a testing technique designed by the author [9,10]. For convenience, it is called the Prism Technique, with reference to the characteristic shape of the samples used. It has been applied successfully for the evaluation of elastic properties of isotopic materials such as metals, and this study proves that it can be generalized to the characterization of highly attenuating media such as mortar and concrete.
Results: The transducer-cell configuration is represented in figure1. The main parts of the cell are two concentric discs of Perspex 5mm thick. The one in the center is fixed to the bottom of the cell, whereas the outside one is made to turn with no play around the fixed disc, making a circle with radius R. The transducer is fixed on top of the ring at a distance R from the center of the disc. The specimen under test (SUT) is centered on the disc with its biggest face opposite to the transducer. The angle α is made to vary between 0° (normal incidence on the main face of SUT), and 90°(transducer beam parallel to the main face).

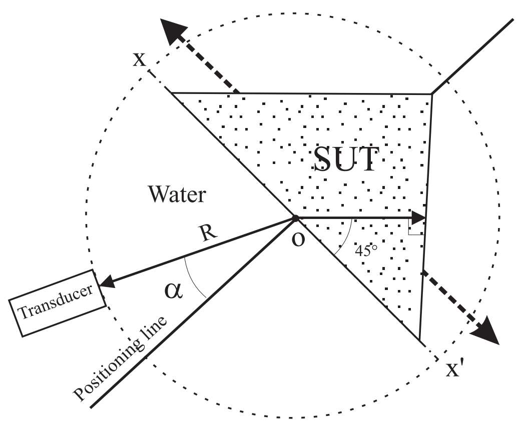

Figure1: Transducer-cell configuration

The velocity of ultrasonic waves is evaluated from the following formula:

$$V_{c,s} = \frac{a}{T_{c,s} - t} \qquad (1)$$

a: side of the prism;
t: time-of-flight of ultrasonic pulse at normal incidence, when total reflection occurs from the main face of the specimen;
Tc,s: time-of-flight of pulse related to both compressional and shear waves when refraction takes place at the critical angles.
Figure2 shows a general view of the ultrasonic apparatus. It consists of the transducer cell, an ultrasonic pulser-receiver, a digital oscilloscope and a laptop computer for data acquisition. Three

transducer frequencies were used for the measurements, namely, 1MHz, 2.25MHz and 5MHz. The prism-shaped specimen could be seen clearly on the right of the figure.

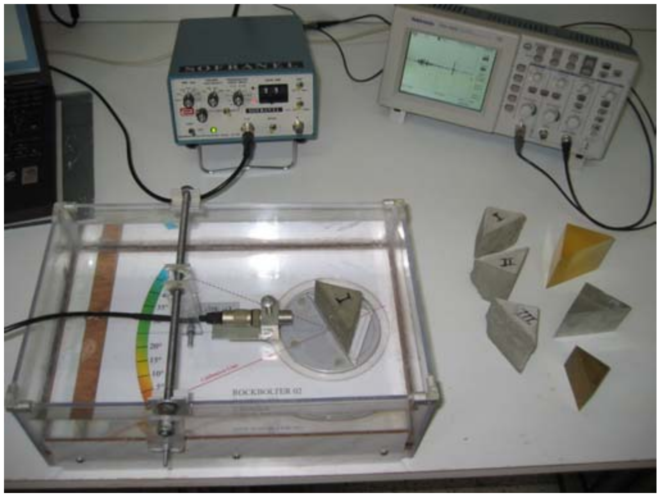

Figure2: General view of the apparatus

A special mould for casting and curing samples was made (figure3). The sides and base of the cube were cut from a sheet of Perspex that is 5 mm in thickness. They were screwed in place with the help of aluminum supports at the corners. This helps in the freeing of the samples after hardening. A thin metal sheet is put across the diagonal of the cube dividing it into two equal prisms. The cube is 50mm wide, and 60 mm high.

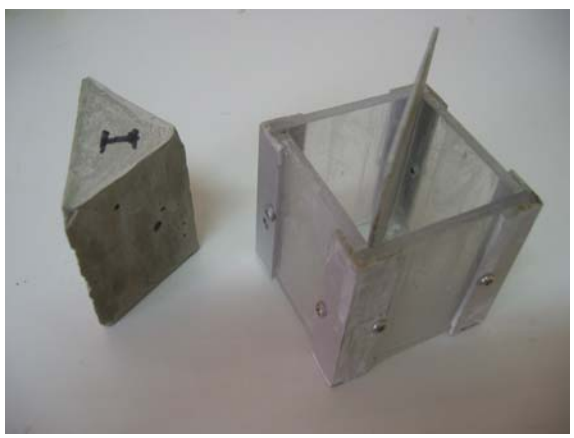

Figure3: The special mould

The procedure for evaluating time-of flights is as follows (figures 4 to 9 are that of sample 6):
At the start of the experiment, the angle α is set to zero. This gives a very clean echo on the oscilloscope related to total reflection from SUT and represents the time delay of the ultrasonic pulse within the water interface. It enables the evaluation of the time of flight t by using the cursors of the digital oscilloscope (measurement accuracy is related to the digital oscilloscope sampling rate of 1 GHz, which gives a definition of 1ns). After that, the angle is increased until the appearance of a second echo (figure4), which is related to compressional waves. It coincides with the first critical angle which gives rise to a refracted compressional wave at an angle of 45°

within SUT. Because the wave impinges at an angle of 90° on the second face it gets totally reflected due to the impedance mismatch between SUT and the water, and thus the beam follows the same path in its way back to the transducer. This enables the evaluation of *Tc*. The angle is increased further, until the second critical angle is reached which gives rise to a third echo (figure5) that enables the evaluation of *Ts*.

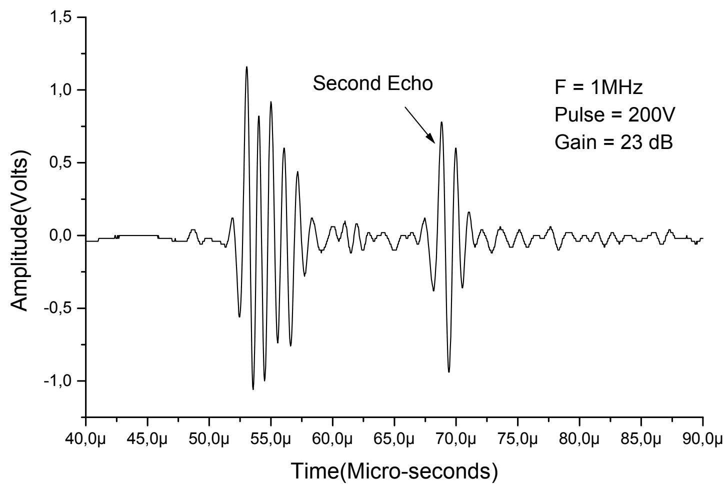

Figure4: waveform related to compressional waves

The vibration that precedes the echo is related to the scattered signal from the main face of SUT. It is an indication of the surface roughness of the sample. The rough the surface, the more pronounced is the vibration.

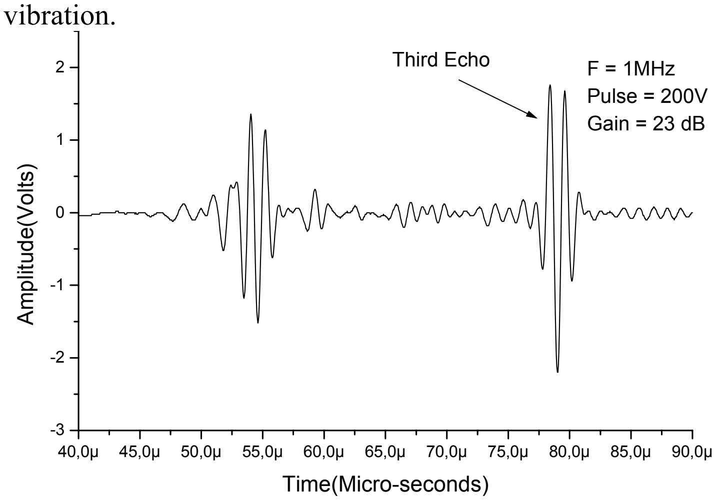

Figure5: waveform related to shear waves

Figures 6 to 9 give four additional waveforms related to the testing of the same sample, but this time with higher frequencies, namely, 2.25MHz and 5MHz respectively. It is quite interesting to note that the echoes decrease rapidly with frequency, which is quite normal since the attenuation increases with frequency. But what is more interesting is the period of the echoes, which increases with frequency. It is especially noticeable in figure 8 and 9. This gives a clear proof that concrete is a highly dispersive medium, and as such it acts as a low pass filter for the ultrasonic pulse. In this case, it seems that the cut-off frequency is equal to 1MHz, since the echoes on figures 4 and 5 seem to have the same period as the testing frequency.

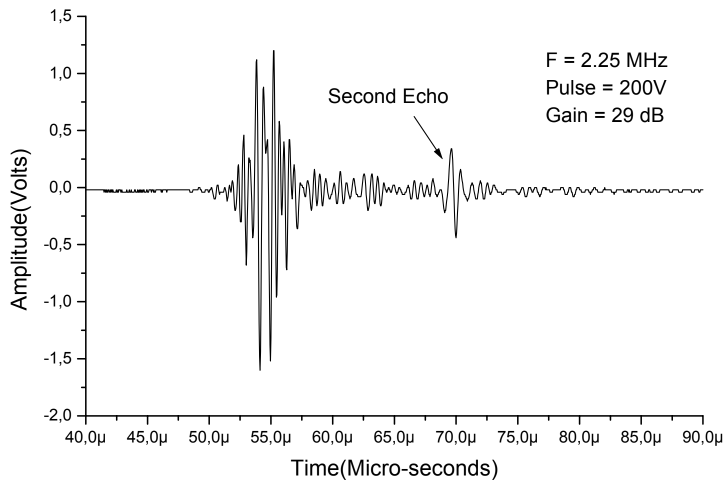

Figure6: waveform related to compressional waves

The scattered signal from the surface of the sample in figures 6 to 9 is much more pronounced than that of figures 4 and 5. This is because the wavelength of the pulse signal approaches the diameter of the flaws present on the surface of the sample, which must be around 1 mm.

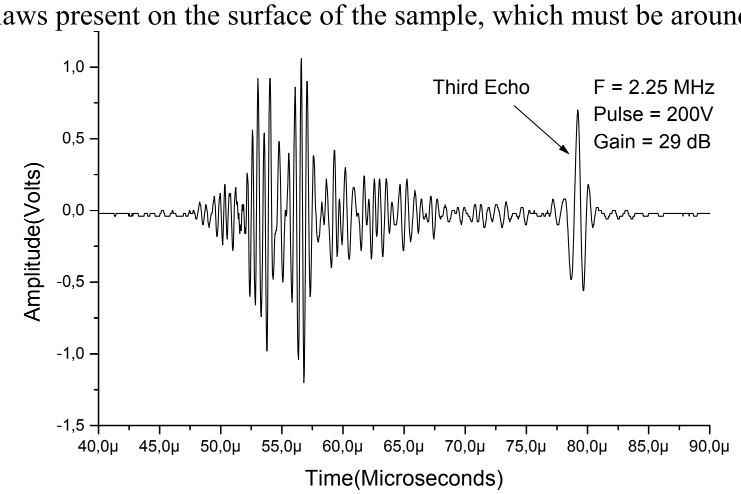

Figure7: waveform related to shear waves

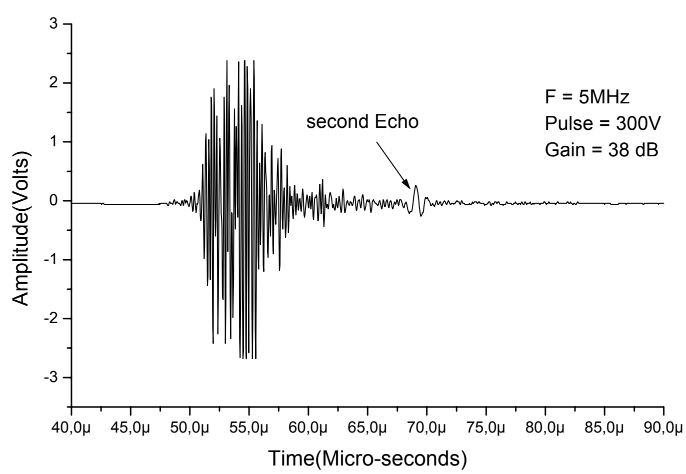

Figure8: waveform related to compressional waves

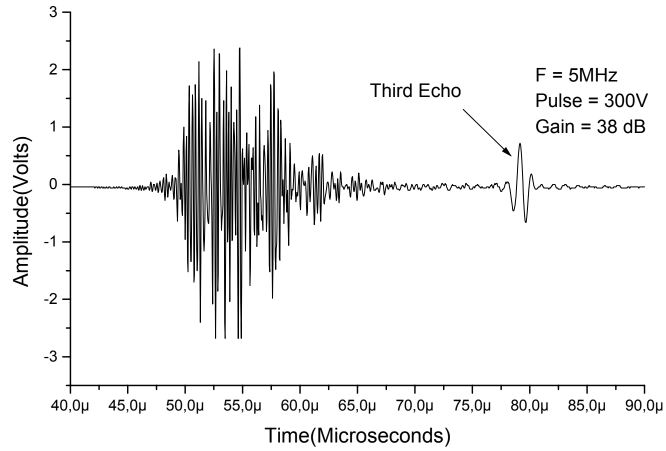

Figure9: waveform related to shear waves

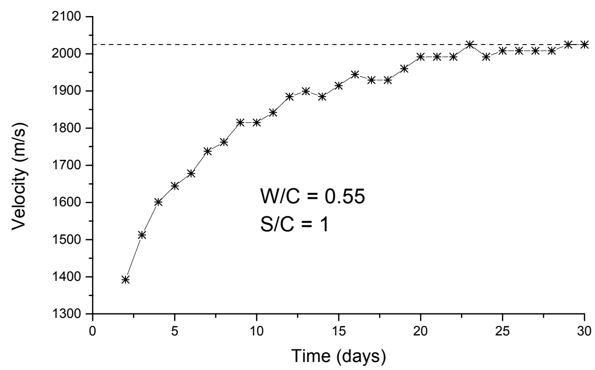

Figure10: variation of compressional velocity with age

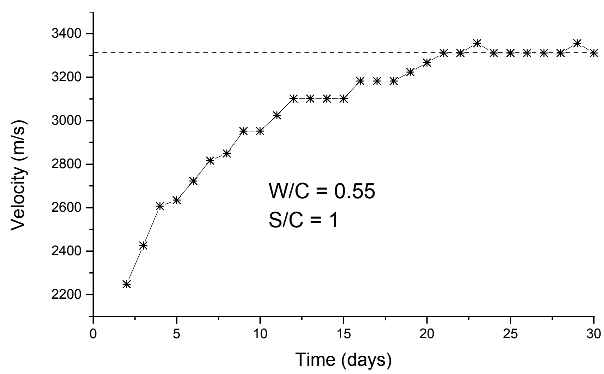

Figure11: variation of shear velocity with age

In figure 10 and 11 the increase of both compressional and shear wave velocities with age is clearly seen. The curve starts to get flat at about day 25, which almost corresponds to the age of maturity of concrete. The most important point here is the repeatability of results, which is noticeable in the quality of the unsmoothed curves.

Table1 shows the elastic constants of six cement and mortar samples (W/C is the water to cement ratio, and S/C is the sand to cement ratio). They are calculated from very well known formulae, which give λ (Lame constant), μ = G (shear modulus), K (bulk modulus), σ (Poisson's ratio), and E (Young's modulus) as functions of the measured *Vc*, *Vs* and the density ρ.

	ρ (Kg/m^2)	***Vc*** (m/s)	***Vs*** (m/s)	**λ** (Gpa)	**μ** (Gpa)	**K** (Gpa)	**σ**	**E** (Gpa)
Sample1 (W/C=0.25, S/C=0)	2000	3610	2129	07.3	08.6	13.0	0.229	21.2
Sample2 (W/C=0.35, S/C=0)	1806	3717	2147	07.1	07.9	12.5	0.236	19.7
Sample3 (W/C=0.45, S/C=0)	1595	3277	1873	05.4	05.3	08.9	0.252	13.2
Sample4 (W/C=0.35, S/C=1)	2133	4083	2418	09.6	11.8	17.5	0.224	28.9
Sample5 (W/C=0.45, S/C=1)	2000	3953	2328	10.0	10.3	16.9	0.246	25.8
Sample6 (W/C=0.45, S/C=1)	1933	3387	2072	05.3	07.9	10.6	0.201	19.0

Table1: Second-Order elastic constants

Discussion: The initial results shown above indicate that the Prism Technique could be used as a reliable testing method for obtaining experimental data that are needed for quality testing and modeling of cement-based materials. The main advantages of this method over other more known ultrasonic techniques and especially the rotating plate technique (which shares some of the features) are as follows:

* There is just one transducer used for measuring the wave velocity of both compressional and shear waves (the latter has even a stronger echo than the former as shown in the figures).

* Easy and uniform coupling between the transducer and the sample, which characterizes immersion-testing methods.

* Formula (1) indicates that the velocities are independent of the incidence angle, which represents a huge advantage over goniometer methods.

* Measurements are temperature compensated, which means that the velocity remains constant for small variations around the ambient temperature. However, the liquid interface could be used to transfer heat to the sample for taking measurements at high temperatures.

* The same configuration could be easily adapted to test samples under high stresses (uni-axial compression, hydrostatic pressure, etc…).

* A careful selection of the transducer frequency, would lead to nice and clean echoes as indicated in the figures, no signal processing is needed, and thus time-of-flights are measured using just the cursors of a digital oscilloscope.

* Despite using just a line marker that indicates the exact placement of the sample in the transducer-cell, figures 10 and 11 show that measurements are repeatable, with minimum errors. This could be improved further by the use of a clamp.

The main disadvantage of this method resides in the new shape of the samples. However, this should not be a problem since the use of cubic samples is already standardized (EN 12390-2, ASTM C31, C192, C511). The same standard could be extended to include the prism-shaped specimens by dividing the cube into two equal halves as shown in figure3.

Conclusions: The main focus of this paper is a novel technique for the measurement of elastic constants of cement-based materials using ultrasound. It represents a significant improvement over similar methods since it enables the evaluation of wave velocities with relative ease and under various conditions of temperature and stress. The special formula used with the apparatus

contains just one variable, namely, the time-of-flight of ultrasonic pulses, which can be measured by means of the cursors of a digital oscilloscope.
Preliminary results show that it is possible to test the different constituents of concrete using high frequency ultrasound. The echoes for both compressional and shear waves are quite clean, and enable the achievement of very accurate and reliable results. This would be a certain advantage in evaluating changes in ultrasonic velocities when samples are subjected to high stresses.

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