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Embedded Early-Age Ultrasonic Testing for Concrete and Shotcrete

Alex Gibson[1], and Daniela Ciancio[2]

[1] AG Acoustic Pty Ltd, Perth, Australia
[2] School of Civil and Resource Engineering, the University of Western Australia, Perth, WA

ABSTRACT: This paper presents results of preliminary laboratory testing with embedded ultrasonic sensors in concrete. These tests were carried out during the development of a field system for monitoring the early-age physical properties in concrete and shotcrete materials. In particular, the design is pertinent to applications in Fibre Reinforced Shotcrete (FRS), commonly used for ground support in underground mine tunnels in Australia, where the determination of early-age properties is critical for establishing safe re-entry times. The embedded system used in these experiments comprises a pair of piezoelectric transducers mounted to an open frame, which is designed to hold them within the concrete at an offset separation of 75mm. The probe is implanted at the time of placement, and connected via wire leads to an external control system. The implanted transducers are configured to excite longitudinal (P) waves, at a nominal resonance frequency of 40 kHz, and P-wave transmission is detectable soon after the initial set time. The data presented herein includes evolution of early-age P-wave velocity. This data is compared to conventional unconfined compressive strength (UCS) and dynamic (low strain) elastic modulus, as specified in ASTM C215, for equivalent batches and curing conditions. The embedded P-wave measurement is functionally equivalent to the conventional dynamic modulus testing procedure, and these results may be further used to infer UCS during the early stages of hydration. The ability to perform in-situ, real time, nondestructive testing offers significant advantages to the safe and efficient use of FRS in underground mining applications.

1 INTRODUCTION

In recent years there has been widespread adoption of the use of fibre reinforced shotcrete (FRS) tunnel linings for providing ground support in underground tunneling operations in the Australian mining industry. In these operations, every time shotcrete is sprayed a safe re-entry time for equipment and personnel is to be established. This must provide sufficient curing time to guarantee the support system has achieved adequate structural integrity, but also permit operations to proceed in a timely, cost-effective manner. The structural resistance of FRS lined tunnel walls is affected by the interaction of rock, bolt and lining elements, and as such a function of multiple independent factors including FRS shear resistance, stiffness and bond strength (Bernard, 2008). However, it is common practice in the industry to use estimated compressive strength of the FRS by proxy for the establishment of permissible re-entry time.

In current practice, quality control tests on FRS at different ages may be carried out at the batching plant site, or at early age using indirect techniques such as needle penetrometers. It is unrealistic to assume that curing conditions of QC samples in the batching plant accurately represent those of material sprayed underground, as logistical difficulties and different environmental factors may well lead to variability of the final product, in-situ. For example, it is plausible that additional dosage of accelerants may be added before the spraying process, and in any case the environmental conditions such as temperature and relative humidity are likely to differ between plant and underground sites. It follows that there is demand for improved capabilities to track the development physical properties of the *in-situ* FRS material.

The use of ultrasonic non-destructive testing (NDT) methods to monitor physical properties of cementitious materials have been subject to extensive scientific enquiry over the past several decades (Keating et al., 1989, Whitehurst, 1951). The main advantage of this approach being that wave velocity, itself contingent on fundamental physical properties, can be determined in a non-destructive, economic manner on a given sample until target parameters are attained.

Although there is a strong positive correlation between concrete strength and ultrasonic pulse velocity (UPV), past research conclusively shows that several factors, including moisture content, aggregate type and content, water/cement ratio and entrained air exert independent influences on the relationship between UPV and strength (Bungey, 1980). Therefore, at full maturity UPV may only provide a quantitative estimate of compressive strength if calibration data is available for the specific mix design in question.

In spite of these shortcomings, UPV is highly sensitive to the development of material properties at early age. During the early stages of hydration, velocity increases more rapidly than compressive strength, and is thus a sensitive indicator of strength gain within the first 3 days, or up to 60% of 28-day strength (Pessiki and Carino, 1988). To this effect, numerous studies on the use of UPV to monitor hydration in various types of cement composites have been carried out in the last decade (Boumiz et al., 1996, Chotard et al., 2001, Sayers and Grenfell, 1993, De Belie et al., 2005). In most cases these tests are limited to laboratory settings by virtue of the instrumentation characteristics, which include surface-coupled transducers, and the well-documented use of a purpose-built container for testing fresh mortar and concrete (Reinhardt and Grosse, 2004).

This paper presents promising results of a novel type of disposable device, designed to be embedded into fresh FRS or concrete at the time of placement. This device uses ultrasonic sensors to generate and detect longitudinal (P) waves whose travel time is measured and related to fundamental material properties. The purpose of the research to date has been to validate the approach of using embedded transducers for efficient, in-situ tracking of relevant physical properties.

2 EXPERIMENTAL METHOD AND PROCEDURES

The following experiments were devised with the primary purpose of validating the proposed approach to monitor in-situ stiffness and strength development using an embedded ultrasonic probe. Testing was carried out using a frame mounted transducer pair, schematically shown in the diagram on the left in Figure 1. The probe consists of a pair of 40 kHz piezo-transducers mounted at a nominal offset separation on 75mm, within an open frame, to be implanted into the fresh material during normal placement operations. The probe is wired through the external surface to the test material to an external control box comprising a high-voltage source and data acquisition system. A typical dataset from this system, over the first 24 hours of curing of a concrete specimen is presented on the right hand side of Figure 1.

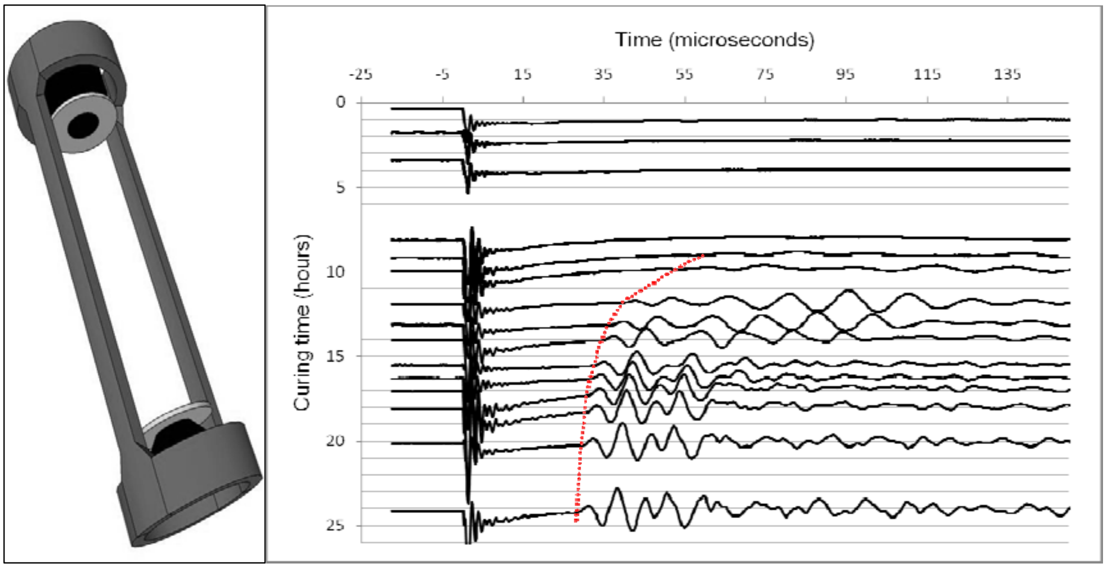

Figure 1 – Schematic depiction of the implanted sensor element (Left) and example ultrasonic dataset at different curing times, showing the onset of hydration at approximately 9 hours (Right), and subsequent reduction in first arrival times.

In the dataset shown above, the detectable P-wave transmission at times prior to 9 hours is negligible, due to high attenuation in the fresh paste. Initial measurable transmissions occur after the time of initial set, as the P-wave velocity of the material begins to increase over the baseline value of 1480m/s (corresponding to the liquid phase of the wet mix). As the hydration process continues, first arrival time decreases in function of increasing P-Wave velocity. Velocity calculations obtained in this study are based on an initial probe calibration in water at room temperature.

The data presented in this paper was obtained using a wet cement mortar mix, detailed in Table 1. The intention of the mix design was to simulate the properties of FRS, while allowing for the material to be cast and vibrated in 0.2x0.1m cylinders for the purposes of laboratory testing and verification. The mix was alternatively prepared with and without fibre reinforcement, using both steel and synthetic fibres.

Table 1. Mix design for testing materials

	Percentage by Mass
Fine Aggregate (<4mm)	35.7%
Sand (Grade 45/50)	34.1%
Portland Cement	17.3%
Water	12.6%
RAD 55 Syntheric Fibre	0.3% (optional)

The embedded velocity measurements were carried at discrete intervals during the first 48 hours of curing for each sample, and compared to traditional stiffness and strength test results, as obtained by cylinder resonance (ASTM C-215) and unconfined compression testing.

3 RESULTS AND ANALYSIS

Under the assumption of a homogeneous, elastic material, P-wave velocity (C_P) is related to fundamental physical properties according to the following equation:

$$C_P = \sqrt{\frac{E(1-\upsilon)}{\rho(1+\upsilon)(1-2\upsilon)}} = \sqrt{\frac{M}{\rho}} \tag{1}$$

were E= Young's modulus, υ= Poisson's ratio, ρ= mass density, and M= bulk elastic modulus.

For cement based materials the above equation is valid for the estimation of dynamic (i.e. low strain) moduli (E_d, M_d), and wavelengths exceeding the dimensional scale of the inhomogeneties presented by aggregate, fibre reinforcement and air voids.

The relationship between P-wave velocity and compressive strength is necessarily empirical, although a variety of commonly used links between stiffness and strength exist in the practice. For example, Australian Standard 3600 document on concrete structures stipulates that, for concrete below 40 MPa, estimated in-situ compressive strength (f_{ci}) is given:

$$f_{ci} = \left(\frac{E}{0.043(\rho)^{1.5}}\right)^2 \tag{2}$$

The results and analysis are presented below in two sections, corresponding to comparison of embedded sensor data with dynamic modulus (E_d), and unconfined compressive strength (UCS) obtained by cylinder compression tests.

3.1 Comparison to Dynamic Modulus

For this series of data, two concrete cylinders were simultaneously cast using the mix design stipulated in Table 1. The first was used for dynamic resonance testing is accordance to procedures outlined in ASTM C-215-08, and an implanted transducer probe was placed in the second cylinder. In each case testing commenced at 10 hours curing time, shortly after the beginning of initial set, at which point it was feasible to carefully de-mould the cylinder for resonance testing, and meaningful acoustic transmission were measurable using the implant.

Cylinder resonance testing was carried out in a configuration that permitted excitation and measurement of the first and second longitudinal harmonic frequencies (f_1, f_2), using a light, wire mounted steel impactor source and a high-frequency microphone receiver as schematically illustrated in Figure 2. From the measured frequencies, dimension and mass of the sample, the development of the dynamic elastic modulus over time was tracked, using the formula stipulated in the standard document:

$$E_d = 5.093\frac{L}{d^2}M(f_1)^2 \tag{3}$$

where d= cylinder diameter, L= cylinder length, M=mass and f_1= 1st longitudinal harmonic frequency.

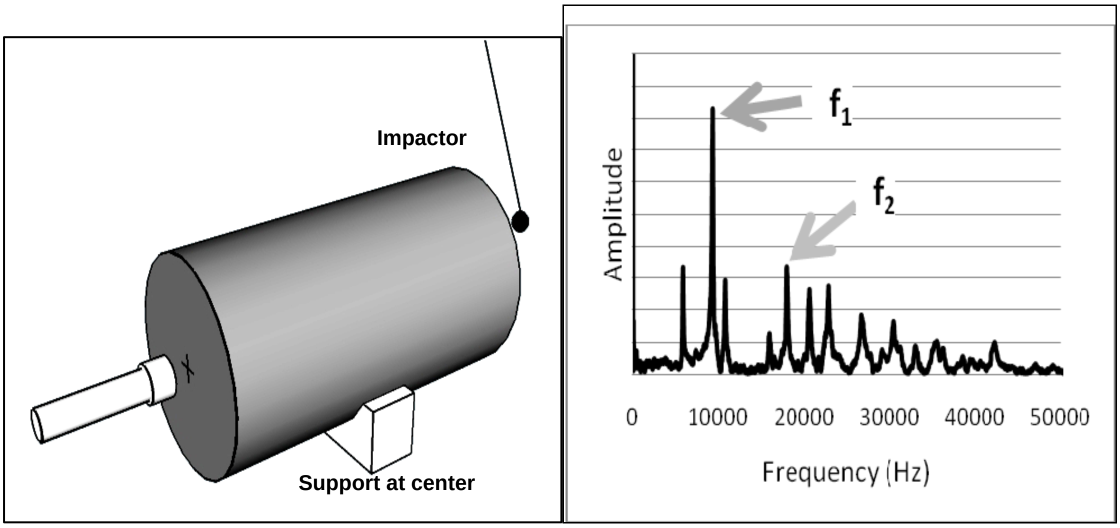

Figure 2 – Cylinder setup for longitudinal resonance testing as per ASTM C215

In addition to dynamic modulus, the time-dependant characteristics of Poisson's ratio were also tracked using the relationship stipulated by Kolluru et al., (2000):

$$\upsilon = A_1\left(\frac{f_2}{f_1}\right)^2 + B_1\left(\frac{f_2}{f_1}\right) + C_1 \tag{4}$$

where: f_1 and f_2 are the first and second longitudinal harmonic frequency, A_1, B_1 and C_1 are dimensional constants (Kolluru et al., 2000)

Following this procedure, a logarithmic trend-line was fitted to measured values of Poisson's ratio, which was found to decrease from approximately 0.35 at 10 hours to a stable value of 0.22 after 24 hours.

In parallel to the resonance testing, in-situ P-wave velocities were measured using the implanted sensor in the second cylinder. For the purpose of comparing the two datasets, measured P-wave velocity was converted to an E_d scale, using the relationship expressed in Equation 5 (derived from Eq. 1).

$$E_d = \frac{\rho (C_P)^2 (1+\upsilon)(1-2\upsilon)}{(1-\upsilon)} \tag{5}$$

This calculation was carried out using a measured value of ρ (2200kg/m^3), and Poisson's ratio assigned via two alternative methods:

1. Variable υ – As fitted to cylinder resonance measurements
2. Constant υ (0.2), as specified by AS3600, in the lack of more specific data.

Thereby, an indication of the sensitivity of E_d, as calculated from velocity, is given for situations where Poisson's ratio is unknown, as may be the case when using the embedded sensor in practical applications. We presume that an accurate value for mass density may be obtained at the batching plant. Figure 3 shows the progression of the two of E_d values obtained from the embedded P-wave velocity sensor compared the independently obtained value obtained from the harmonic resonance testing with the other cylinder.

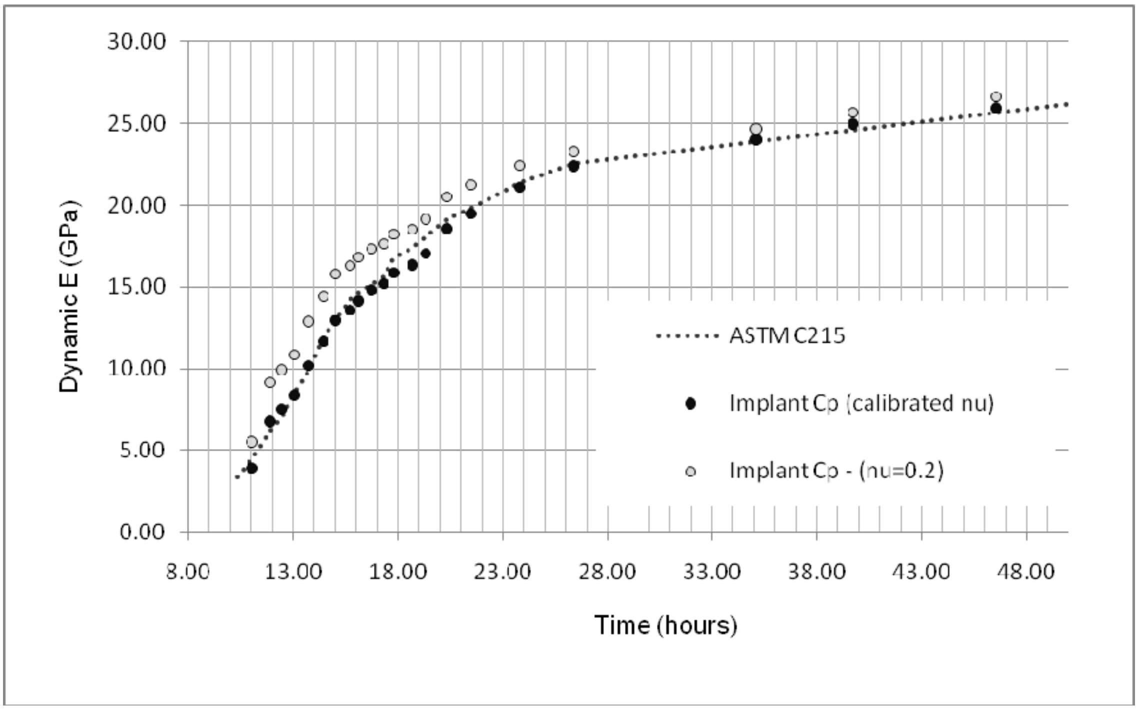

Figure 3 – Progression of dynamic elastic modulus as determined by harmonic cylinder resonance (line), and embedded P-wave velocity using measured and assumed values of Poisson's ratio (dots).

3.2 Estimation of Compressive Strength

The second relevant engineering property compared to the in-situ velocity measurements was unconfined compressive strength, obtained by the destructive testing of a series of concrete cylinders. Two series of tests were carried out, using a plain concrete mix in the first, and a similar mix with added synthetic fibre reinforcement in the second, proportions as specified in Table 1. In parallel to in-situ velocity testing in a separate sample, two compression tests were carried out at 10, 15, 20, 25, 36 and 48 hours curing time, for each batch.

Compressive strength can be empirically calibrated to P-wave velocity, and the relationship is mix-specific at full maturity, given the independent influences of various factors mentioned earlier. However, many authors cited in this paper have determined that P-wave velocity is relevant to establishing initial set times, and tracking compressive strength at early age, while the material properties are developing at a rapid pace.

Pessiki and Carino (1988) propose an empirical relationship based on experimental data, relevant to the period when the strength-velocity relationship is most sensitive, which they found to be in the first 3 days or up to 60% of design strength:

$$UCS[MPa] = 0.0788\left(\frac{C_P[km/s]}{200}+1\right)^{306.2} \tag{7}$$

Alternatively, a hypothetical strength-velocity relationship may be derived from the empirical link between strength and stiffness, as provided by Standards Australia (AS3600-2009) or other agencies. For instance, equations 2 and 5 may be used in combination to derive an indirect strength-velocity relationship, with the additional (significantly incorrect) assumptions of constant Poisson's ratio and lack of distinction between static and dynamic elastic modulus.

The distribution of measured P-wave velocity vs. average compressive strength for samples aged between 10 and 48 hours is presented in Figure 4, alongside the empirical relationships proposed by Pessiki and Carino (1988), and one indirectly derived from the suggested stiffness vs. strength approximation (AS3600-2009).

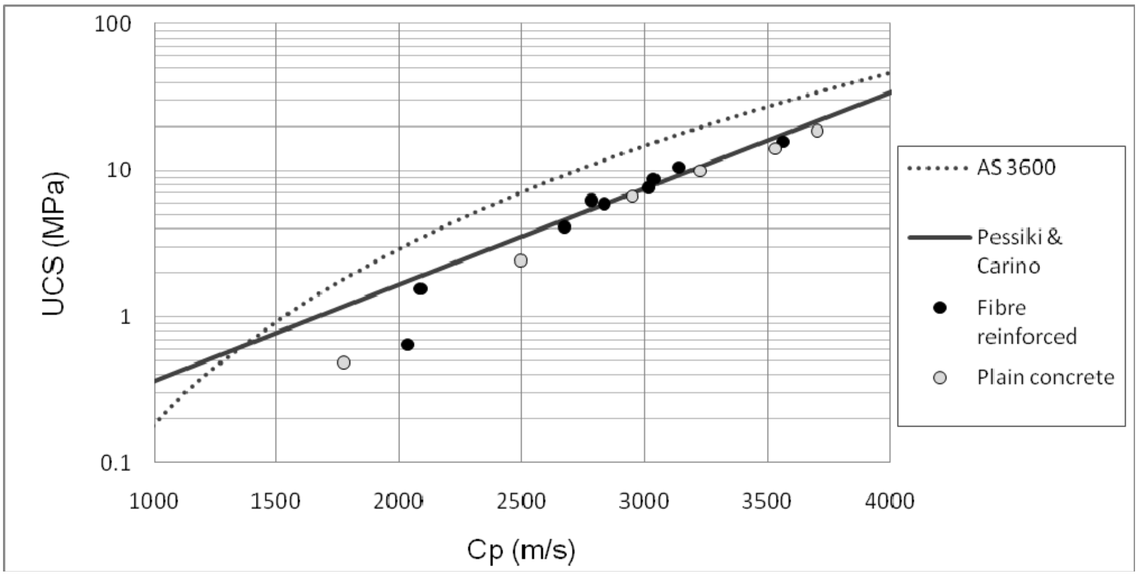

Figure 4 – Distribution of velocity vs. average compressive strength between 10 and 48 hours, plus empirical relationships by Pessiki and Carino (1988) and derived from (AS3600-2009).

4 DISCUSSION, CONCLUSIONS & FUTURE WORK

Although the proposed use of UPV for monitoring development of material properties has received much past attention, this paper demonstrates a novel approach of performing such measurements *in-situ,* using field-worthy equipment and a disposable ultrasonic probe. The work herein presents data derived from a prototype embedded system, which was able to detect P-wave arrivals in concrete after the initial set time, and was not adversely affected by the presence of synthetic or steel fibre reinforcement.

For purposes of predicting early-age stiffness (E_d), the procedure is functionally equivalent to ASTM C215 in terms of the nature of the dynamic, low-strain physical measurements. In the case of embedded velocity measurements, an accurate estimate of Poisson's ratio is required to convert from bulk modulus M_d to elastic modulus E_d. In these experiments the value of Poisson's ratio was found to vary significantly in the initial 24 hours of curing, from approximately 0.35 to 0.22, with a corresponding effect on the precision of E_d values. The assumption of a constant value of 0.2, as prescribed by AS-3600, was deemed unsatisfactory for analysis of early-age physical properties, within the first 24 hours.

We believe further research is merited on the time-dependence of Poisson's ratio at early age, in particular the possibility of formulating a direct correlation to P-wave velocity.

For the purpose of using P-wave velocity to predict early-age strength, the experimental data obtained in this study shows good correlation to the empirical relationship independently developed by Pessiki and Carino, (1988) for values of unconfined compressive strength higher than 4 MPa and up to 48 hours maximum curing time (the limit of this particular study).

For compressive strength values between 1 and 4 MPa, which are relevant to FRS applications, greater variability and deviation from the proposed empirical relationship was observed. It should be noted that the most significant source of statistical variability in this range is attributable to cylinder compression test results, rather than the in-situ velocity measurements. The nature of the velocity vs. strength correlation within this lower range is a matter for further research.

The derivation of an approximate velocity-strength relationship using empirical conversions suggested by AS-3600 would tend to over-predict strength, and were deemed inadequate for this type of application.

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