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Noncontact ultrasonic diagnostics in concrete: A preliminary investigation

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Abstract

The use of ultrasonics is well-established in concrete diagnostics. Most current systems use narrow-bandwidth piezoelectric transducers, which must be in contact with the concrete surface. New ultrasonic nondestructive testing (NDT) systems combine electrostatic broadband transducers and signal processing techniques such as pulse compression to improve signal-to-noise ratios (SNRs). This permits air-coupled, noncontact (NC) operation which has many advantages. Preliminary experiments with low-power NC equipment, designed for foodstuffs and packaging, indicate that diagnostics can be performed in this manner through at least 75 mm of concrete. The speed-of-sound versus strength relations thus determined differ from those measured previously since the NC system is more sensitive to paste properties than aggregate properties while the converse tends to apply for traditional equipment. There is significant scope for optimising the NC system to achieve greater penetration and diagnostic capability.

Keywords: Ultrasonics; Compressive strength; Concrete

1. Introduction

Ultrasonic pulses have been used in research for diagnostic examination of concrete since the late 1940s [1]. The now ubiquitous PUNDIT apparatus was developed in the early 1970s and relationships between cube strength and ultrasonic pulse velocity were established [2]. The use of the apparatus for on-site diagnostics developed relatively quickly [3]. Determination of pulse velocities has become part of many national standards for concrete testing [4]. Similar equipment is still widely used, e.g. for nondestructive assessment of cumulative damage in concrete exposed to elevated temperatures [5] or triaxial stress [6].

Research into improving ultrasonic diagnostics of concrete continues. Some investigators [7] have used high-frequency ultrasound (0.5–1 MHz cf. typical 50 kHz of the PUNDIT) to characterise cover degradation. They found that the attenuation of the signal was much more sensitive to degradation at these frequencies, particularly for surface waves. Other recent investigators have modelled diffusion of ultrasound in concrete and attempted to use the ‘incoherent’ field, generated by scattering from the material microstructure, as a diagnostic tool [8]. They noted that inadequacies in theory and data analysis hamper the application of this approach to complex heterogeneous materials such as concrete. Synthetic aperture focussing techniques (SAFT), where arrays of several transducers are used and signals reconstructed using computers to provide images of internal defects [9,10], have also received much recent attention.

Most of the equipment in current use for ultrasonic studies in concrete has several basic disadvantages. First, the need for physical contact between the concrete surface and the transducers is inconvenient. Concrete surfaces are rarely smooth enough for simple contact to provide sufficient acoustic coupling. Extensive surface preparation and/or couplant gels are required. The force with which the transducers are clamped to the surface (normally by hand) also affects the measured pulse velocity. Most equipment requires that both transmitting and receiving transducers be in contact with the concrete [5,8]. Some require that only a transmitting transducer is in contact, the receiving being carried out using scanning laser vibrometers [11], which are of questionable practicality in field applications. Transducers in SAFT arrays act as transmitters and receivers alternately but still require good surface contact [9,10]. Secondly, the transmitting transducers generally used tend to be of the resonant piezo-

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electric type. These are excited with a transient or delta-function pulse and vibrate at their natural frequency. Thus, the sample is only exposed to a very limited range of frequencies in a single test. To examine the response to different frequencies, a range of transducers is required. Efforts have been made to deliver pulses, known as 'chirps', containing a controlled range of frequencies but detection required laser interferometry, owing to the limited sensitivity of piezoelectric transducers in broadband operation [11].

Ultrasonic nondestructive testing (NDT) research applied to homogeneous materials has recently concentrated on use of broadband acoustic transducers, based on electrostatic principles, that can accurately emit chirps defined by signal generators rather than resonant narrow-band signals. A rigid conducting backplate and a thin membrane film are arranged to form a capacitor. Applying a modulated voltage causes vibration in the membrane, generating ultrasound; changes in charge across the membrane can be used for detection [12]. As well as the exposure to a wider range of frequency and associated increase in diagnostic possibility, using broadband chirps allows a signal analysis technique known as pulse compression to be used to significantly improve signal-to-noise ratios (SNRs) [13]. In pulse compression, the received signal $C_T(t)$ is first filtered such that all frequencies other than those contained in the original chirp (e.g. for a 250-kHz bandwidth chirp centred on 250 kHz, all the frequency components below 125 kHz or above 375 kHz) are removed. This filtered signal is then cross-correlated with the input signal $C(t)$ to give the compressed pulse $P(t)$. Cross-correlation involves incrementally time-shifting $C_T(t)$, multiplying it with $C(t)$ and plotting the result versus the time-shift. The value of $P(t)$ will be nominally zero except at a single time-shift where a sharp peak will be evident; this time-shift value represents the time-of-flight of the signal. Using this technique, the SNR can be improved enormously such that signals can be easily recovered from well below the noise floor of the detector. Time-of-flight accuracy is improved since the signal will only correlate at a single well defined time-of-flight.

The use of pulse-compression and broadband transducers, with concomitant increase in SNR, has permitted the use of air-coupled—i.e. noncontact (NC)—ultrasonic techniques for diagnostics in materials, which are of particular value in applications where contact is undesirable, e.g. food [14]. Given the relatively rough surface of most concrete components and the resultant difficulties in ensuring uniform acoustic contact between transducers and sample, an NC technique would have significant advantages.

The aim of this project was to investigate the possibility of using air-coupled ultrasound with advanced pulse compression and signal analysis techniques as a means of performing NDT on concrete. Results were compared with those from traditional PUNDIT tests.

2. Experimental

Four concrete mixes with target 28-day strengths of 30, 40, 50, and 60 N mm^{-2} were prepared with Portland cement, sand, and 20-mm coarse limestone aggregate. Compressive strength tests on standard 100-mm cubes were carried out in triplicate after 7 and 28 days of water curing, each cube having been previously assessed using a PUNDIT. At the same time, 100×100 mm slices of various thickness up to 75 mm were tested using an air-coupled ultrasound setup, a schematic for which is shown as Fig. 1. The heart of the system is the NCA1000 pulser/receiver unit (VN Instruments) with on-board digital signal processor (DSP) to synthesise output pulses for source excitation and run embedded pulse-compression code for online processing of received signals. The transducers were of a novel metallised polymer film/micromachined silicon backplate capacitance design described in detail in a previous work [12]. At least six measurements per sample were taken with the NC setup. Time-of-flight (and thus speed of sound) in the samples was measured by both systems and correlated with cube strength.

3. Results

The driving signals (a) and output waveforms (b), together with respective spectral analyses, for the transmitting transducer generated by both systems are compared in Fig. 2. The PUNDIT 'pings' its piezoelectric transducer with a 3-μs transient pulse; the transducer then vibrates according to its natural resonance (at about 50 kHz according to the FFT, with some higher harmonics). The NCA1000 delivers a tuned Hanning 'chirp' (in this case centred on 250 kHz with 250 kHz bandwidth), which the capacitance transducer accurately reproduced. This bell-shaped (i.e. both amplitude and frequency modulated) chirp removes the rippled band-edges that characterise ordinary frequency-modulated chirps previously used in

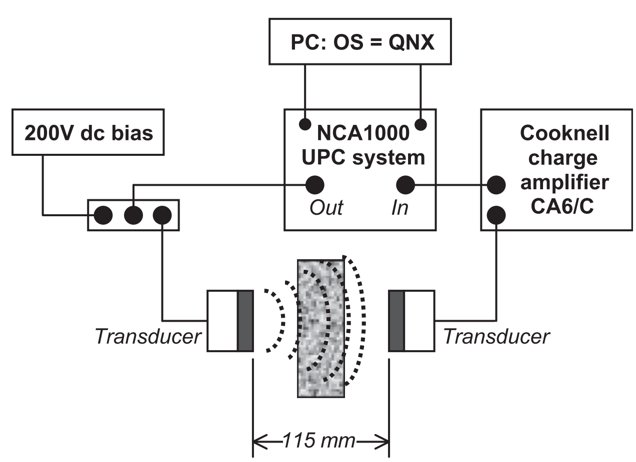

Fig. 1. Schematic of air-coupled ultrasound testing apparatus.

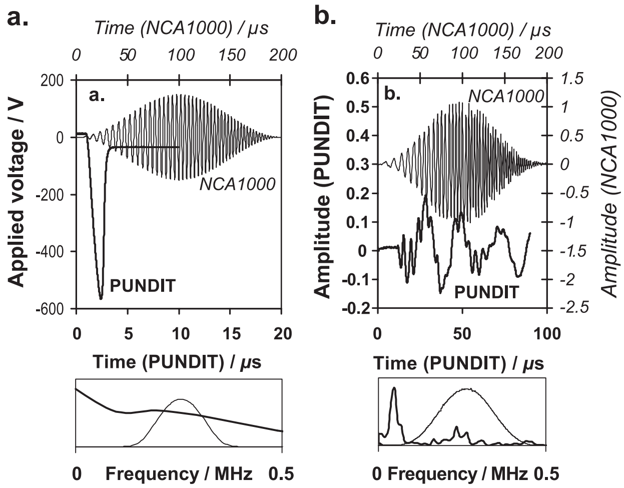

Fig. 2. Transmitting transducer voltage drive input (a) cf. received ultrasonic transducer output (b) for PUNDIT and NCA1000 systems; time domain (top) and FFT spectral analysis (bottom).

concrete NDT [11], which reduce the efficiency of the waveform.

Preliminary results showed that, even with existing low-power equipment (designed for use with thin, homogeneous materials, e.g. food packaging), it was possible to receive an air-coupled signal through at least a 75-mm thickness of C60+ concrete quite easily. It was also established that there were no 'second-order' thickness effects, thus the data for different thicknesses were grouped. Fig. 3 shows the correlation between cube strength and speed of sound. As expected over this range of strengths, the PUNDIT tests returned an approximately linear relationship between strength, S, and speed of sound, c, in the samples with $\Delta c/\Delta S$ of about 13 m/s/MPa. The NC tests also recorded a strong correlation, but with considerably greater scatter (especially at higher strengths) and with $\Delta c/\Delta S$ of about 45 m/s/MPa. The NC method returned much lower values for c for low-strength (< 50 MPa) concrete than the PUNDIT but both systems returned similar values for higher-strength concrete.

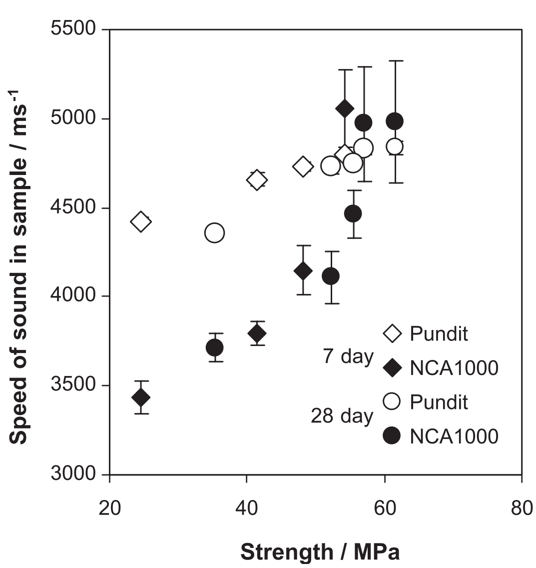

Fig. 3. Speed of sound in concrete versus strength; air-coupled testing (NCA1000), cf. PUNDIT.

4. Discussion

The main objective of the study was to show that NC NDT on sizeable concrete samples was possible; the marked difference in the strength versus speed of sound relationship returned by the two systems was unexpected. One possible explanation for the discrepancy is a coupling effect. The steel PUNDIT transducers in contact with the surface are stiffer and denser than both phases of the concrete, i.e. the aggregate or the paste. Thus, preferential acoustic coupling will occur between the steel and the stiffest/densest of the two phases, i.e. the aggregate. The ultrasonic pulse will tend to be transmitted along paths that maximise aggregate content. Since the speed of sound is greater in the aggregate than in the paste, the measured speed of sound is relatively high. In the NC system, the contacting medium is air, which is less stiff and less dense than either concrete phase. Thus, the ultrasound will be preferentially transmitted through the paste and a lower speed of sound measured. As the strength of the concrete is increased by lowering the w/c ratio, the stiffness and density of the paste approaches that of the aggregate and the discrepancy between the returned speeds is reduced and eventually becomes insignificant. To test this thesis, a number of specimens were made with different aggregate contents but constant water/cement ratios (hence constant paste properties) and tested with both systems after 8 days of water curing. The results are shown in Fig. 4. It was found that there was little correlation between aggregate

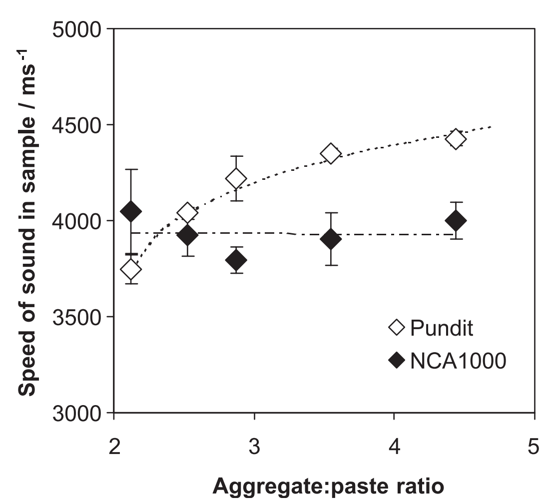

Fig. 4. Speed of sound in concrete versus w/w aggregate/paste ratio at constant w/c ratio (0.5); air-coupled testing (NCA1000), cf. PUNDIT.

content and the speed of sound measured using air coupling, but a strong positive correlation between aggregate content and speed measured using the PUNDIT. The increased scatter in the air-coupled (NCA1000) results, cf. the PUNDIT results, is probably caused by the smaller aperture of the NC transducers (10 mm, cf. 50 mm diameter, respectively). The larger PUNDIT transducers will 'average out' inhomogeneities in the relatively large area under inspection, whereas the NC transducers will be sensitive to local effects, e.g. large aggregate particles. Why the magnitude of the scatter increased with concrete strength is not clear.

5. Conclusions

It has been shown that low-power NC ultrasonics can be used as a nondestructive diagnostic technique for concrete up to 75 mm thick. The correlation between strength and speed of sound thus measured is strong but differs from that measured using traditional equipment. The discrepancy is due to preferential coupling effects; the NC system is more sensitive to paste properties and the PUNDIT is more sensitive to aggregate. Since the properties of concrete are more highly dependent on the state of the paste than the aggregate, the NC method would appear to offer a more sensitive method for diagnostics in concrete. NC operation removes the need for surface preparation, couplants and the operator error associated with the contact transducers and may be desirable in some hazardous applications, e.g. monitoring of encapsulated nuclear waste. There is significant potential for optimisation and increased penetration through using higher-power transducers and investigating a range of chirp frequencies, bandwidths and shapes.

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