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Ultrasound frequency analysis for identification of aggregates and cement paste in concrete

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ABSTRACT

The aim of the present study was to identify specific frequencies related to aggregates and cement paste during concrete hydration, by performing a Fourier analysis of the ultrasonic response of concrete specimens to different excitation frequencies. This identification will reduce the high influence of aggregates in the ultrasound signal analysis, enabling a better assessment of changes occurring in the cement paste. Thirty-five cylindrical specimens with a diameter of 100 mm and a length of 200 mm were cast with a water to cement ratio = 0.60. Thirty specimens were destructively tested at 1, 3, 5, 7, 14 and 28 days for their compressive strength. The remaining five specimens were non-destructively tested at 1, 3, 5, 7, 14, 28 and 56 days using longitudinal and transversal ultrasonic wave transducers with frequencies from 50 kHz to 500 kHz. Analysis of the evolution in frequency observed in the specimens identified variations related to progressive hydration of the cement paste, in contrast with the invariant behavior of the inert aggregates. Results show that it is possible to distinguish the behavior of cement paste and aggregates in the frequency domain. As a consequence, it should be possible in future research to evaluate more efficiently different phenomena that affect only the cement paste.

1. Introduction

Non-destructive techniques are used to evaluate the quality and performance of concrete structures without causing any structural damage [1,2]. The Ultrasonic Pulse Velocity (UPV) is one of the most used non-destructive techniques for measuring mechanical properties of concrete during hydration and evaluating damage in concrete structures [3–6]. Previous studies have found an exponential relationship between the compressive strength of concrete and the UPV, which has shown to be barely sensitive to small variations in strength at late ages [7,8]. Concrete is basically composed of a mixture of cement, water, fine and coarse aggregates that produce a heterogeneous material. The heterogeneities produced by the coarse aggregates strongly influence the propagation of ultrasonic waves, depending on the frequency studied [9]. Therefore, the analysis of changes in an ultrasound wave propagated across a concrete specimen at selected frequencies, may be used to extract information on processes occurring mainly in the cement paste, for example during hydration or during chemical reactions in the cement paste with aggressive species (e.g. chlorides and CO_2).

When a wave propagates, its phase and amplitude are modified depending on the transmission medium. The propagation of ultrasound waves is affected by the heterogeneities of concrete in different ways. The influence depends on the wavelength and the size of the concrete components [10]. In previous studies, this behavior was used to characterize entrained air voids in cement paste [11]. Other studies have employed the propagation velocity of the wave attenuation to estimate cracking [12–14], voids, the setting process [15,16] and the compressive strength of concrete. Taking advantage of these properties, several experimental studies using through-transmission ultrasonic measurements of longitudinal or transversal waves have been carried out on concrete to determine the setting time of concrete [4,17]. It has also been found that the attenuation of the ultrasound signal is different for cement paste, mortar and concrete in a frequency range of 50–1000 kHz [18,19]. Additionally, the setting process of cement pastes has been analyzed by the response of ultrasonic waves using the frequency spectrum of the Fast Fourier Transform [20].

Based on the aforementioned, it is assumed that, depending on the frequency band used, the response of concrete materials to ultrasonic waves contains more information than is reported. Therefore, this study focuses on developing a method for the identification of frequency bands associated with aggregate and cement paste during the hydration process of concrete. This identification would enhance the study of process which occur only in

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the cement paste such as hydration, chloride penetration and binding as well as carbonation produced by the chemical reaction between the CO_2 and $Ca(OH)_2$ dissolved in the pore fluid.

2. Experimental procedure

2.1. Materials

Mexican ordinary Portland cement class 30RS (ASTM C150 Type I or EN 197-I, with chemical composition shown in Table 1) was used. The coarse aggregate was limestone with a maximum size of 13 mm. The fine aggregate was river sand with a fineness module of 2.67. Thirty-five cylindrical specimens measuring 100 mm in diameter and 200 mm in height were cast with a w/c ratio of 0.60. After 1 day, the specimens were stripped and moist-cured in a saturated lime solution at 23 ± 2 °C for 56 days, according to the standard ASTM C31 [21]. Moist curing with saturated lime solution avoids leaching of the calcium hydroxide from the cement paste, which otherwise would increase the porosity and reduce the density and elastic modulus of the cement paste.

2.2. Methods

2.2.1. Compressive strength

Thirty specimens were tested at 1, 3, 5, 7, 14, and 28 days to measure their compressive strength using a 120 ton compression machine.

2.2.2. Ultrasonic measurements

Five specimens were tested at 1, 3, 5, 7, 14, 28 and 56 days. The ends of the specimens were cut with a concrete saw in order to obtain a smooth surface. A record was maintained of their responses in through-transmission to longitudinal and transversal ultrasonic waves, generated by eight pairs of transducers with frequencies ranging from 50 kHz to 500 kHz. The position of the transducers and their applied pressure were kept constant during the experiment. Petroleum jelly was used as coupling agent to improve wave transmission. The excitation signal was generated by a 5058PR pulser/receiver with a voltage of 200 V and damping of 40 dB. The UPV was also obtained for the thirty specimens before compressive strength testing.

3. Wave analysis

3.1. Signal processing

The aim of the proposed method for analyzing the ultrasound signals is to identify frequency bands over time associated with aggregates and cement paste in hydraulic concrete. One of the features of concrete is that the properties of the hydrating cement paste vary over time as opposed to those of aggregates which are invariant over time. The Fast Fourier Transform (FFT) has been recognized as a standard signal processing technique for analyzing ultrasound signals [22]. The first step in the proposed analysis is to calculate the time-discrete Fourier Transform (TDFT) of the ultrasound signal $f(n\Delta t)$, according to Eq. (1).

$$\mathrm{F}(\mathrm{k}\Delta\omega) = \frac{1}{2\pi}\sum_{n} f(n\Delta t)e^{-i(2\pi kn/N)}\Delta t \tag{1}$$

where T is the duration of the ultrasound signal, discretized at a sampling rate $\Delta t = T/N$, and $k\Delta w$ are the resulting discrete frequencies.

A window of $\mathrm{F}(\mathrm{k}\Delta\omega)$ is subsequently selected from the frequency response function of the transducers with an intensity greater or equal to 6 dB, as specified by the ultrasound transducer manufacturer.

$$\mathrm{G}(\mathrm{k}\Delta\omega) = \begin{cases} F(k\Delta\omega), & k_1 \leqslant k \leqslant k_2 \\ 0, & elsewhere \end{cases} \tag{2}$$

The evolution in time of the seven spectra obtained (1, 3, 5, 7, 14, 28 and 56 days) from ultrasound measurements $\mathrm{G_i}(k\Delta\omega)$, where $1 \leqslant i \leqslant 7$, was analyzed for the identification of frequency bands associated with aggregates or cement pastes. This analysis consists of the correlation of variations along time of every frequency amplitude $|\mathrm{G_i}(k\Delta\omega)|$, with a function that describes an assumed behavior of aggregates or cement pastes. For the identification of frequencies k_a associated with aggregates, a correlation with a constant function different from zero was performed. In the case of frequencies k_p related to cement pastes, they were correlated with the evolution in time of the compressive strength that indicates the progress of cement hydration, Fig. 1. The compressive strength was determined according to the standard ASTM C39/C39M-16 [23]. The load was applied at a rate of 0.25 ± 0.05 MPa/s (35 ± 7 psi/s).

Evolution of the compressive strength of concrete is closely related to density (ρ) changes in the hydrating cement paste, influencing the propagation of the ultrasonic waves [2]. Constant density of limestone aggregate (ρ = 2.60 kg/m^3), of sand (ρ = 2.57 kg/m^3) and of saturated concrete were obtained, Fig. 1. A strong correlation coefficient (R = 0.98) states the evident similarity between density and compressive strength evolution in time. Similarly, a strong correlation (R = 0.984) was found between the compressive strength of concrete (f′c) and UPV.

Once the assumed behavior for cement paste was identified, a threshold was defined as the mean value of the correlations obtained, with a precision of 0.001, for the identification of cement paste or aggregates, assuming a normal distribution for those values. The frequencies with correlations stronger than the threshold were assumed to be related to the corresponding behavior of cement paste or aggregates. As the thresholds for both

Table 1
Chemical composition of main oxides for the Ordinary Portland Cement (OPC) used.

Main oxides components	%
SiO_2	21.1
Al_2O_3	3.7
Fe_2O_3	4.5
CaO	61.9
MgO	1.8
K_2O	0.3
Na_2O	0.1
SO_3	1

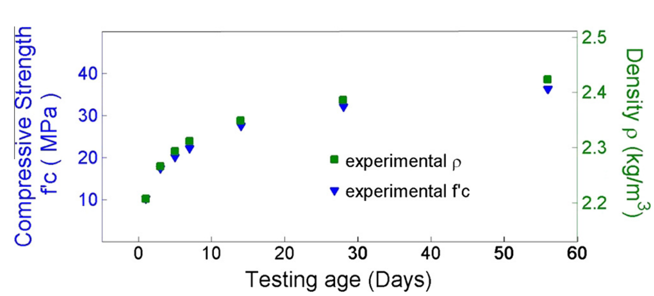

Fig. 1. Evolution of concrete compressive strength (blue triangle) and saturated density (green squares) versus age of concrete w/c = 0.60. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)