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Short communication

Drying shrinkage in concrete assessed by nonlinear ultrasound

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ABSTRACT

This research develops a nonlinear ultrasonic (NLU) technique, second harmonic generation (SHG), to monitor the time-dependent microstructural evolution and shrinkage in concrete over a period from 28 to 55 days of age. Drying shrinkage by moisture migration from concrete to its environment causes stress and microcracking and can lead to larger crack formation, which compromises performance. Here, the process of drying is monitored by the SHG method using nonlinear Rayleigh surface waves to obtain the acoustic nonlinearity parameter. The results show large changes in the measured acoustic nonlinearity parameter which is attributed to damage generated during drying shrinkage. Finally, the measured acoustic nonlinearity parameter is used to compare the microstructural condition in hardened concrete as affected by shrinkage mitigation (through the use of shrinkage-reducing admixture) and crack filling (or self-healing) by carbonation.

1. Introduction

Understanding the physical phenomena underlying the propagation of nonlinear ultrasonic waves has the potential to determine the structural health of concrete structures. The heterogeneity of porous materials like concrete has a direct connection with their nonlinear ultrasonic properties. That is, nonlinear ultrasonic waves are capable of detecting microcracks that determine the nonlinear coefficients of the constitutive relationship for these porous materials [1–7]. Of particular interest for the evaluation of concrete structural health is the characterization of the time-dependent evolution of microstructure and environmental interactions [8–11].

In an environment which is dry relative to concrete, water evaporates to the air. As pores empty, tensile stresses are generated, and when the tensile capacity – which can be limited in cement-based materials, and particularly so at earlier ages – is exceeded, cracking develops. It is therefore expected that microcracks are significantly developed by drying shrinkage, and because the drying front develops from an exposed surface, much of the source of microstructural nonlinearity will be concentrated near these surfaces in drying environments.

Here, a Rayleigh surface wave is used in a second harmonic generation (SHG) technique to monitor changes in the microstructure during drying shrinkage. The physical principle of the SHG method is that a propagating ultrasonic wave with a fundamental harmonic frequency, ω interacts with the internal microstructure (including the damage state) and some energy of the fundamental harmonic wave is converted to generate a second harmonic wave with the frequency 2ω. The amplitude of the second harmonic wave is directly dependent on the sources of the material nonlinearity such as microcracks [12]; the SHG method using Rayleigh surface waves is capable of quantifying microcracks in concrete. The relationship between this material nonlinearity and a propagating ultrasonic wave is

$$\beta = \frac{A_2}{{A_1}^2 x} \tag{1}$$

where A_1 and A_2 are the amplitudes of the fundamental and second harmonic waves, x the propagation distance, and β the relative acoustic nonlinearity parameter [13,14]. This research performs the SHG measurement by following the procedures described by [3,4]. Note that microcracks are a strong source of acoustic nonlinearity in materials [12,15].

It is important to note that previous research has demonstrated that nonlinear acoustic parameters are more sensitive to microscale damage than conventional linear acoustic parameters [5,13,14,16,17]. It has been well demonstrated that the SHG method with Rayleigh surface waves is suitable for assessing the microstructure in concrete, giving rise to new tools for interpreting the current damage state of concrete [3,4]. This SHG technique has an advantage for evaluating defects concentrated near the surface as Rayleigh waves penetrate the surface on the order of their wavelength; the wavelengths of the fundamental (~5 cm) and second (~2.5 cm) harmonic waves are large enough to characterize the region of interest where this evaporation is occurring, and thus provide a linkage between the evolution of microscale damage and the acoustic nonlinearity parameter.

However, these SHG measurements are not wavelength limited; the wavelength of these nonlinear ultrasonic waves does not need to be of

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the same (micrometer) length scale to sense microscale damage. This is in direct contrast to linear ultrasonic measurements (wave velocity and attenuation coefficients) where the ultrasonic wavelength must be on the order of the microscale damage to ensure sensitivity to this damage. This physical restriction has severely limited the application of linear ultrasonic techniques to quantitatively characterize microscale damage in concrete because of the extreme scattering from the concrete microstructure (such as coarse aggregates) at higher ultrasonic frequencies.

The objective of this paper is to obtain insights into the time-dependent transition of the microstructure in hydrated concrete using the SHG method, including specifically characterizing the evolution of microscale defects during drying shrinkage over a one-month drying period. In addition, this research uses the SHG method to monitor the microstructural influences of: (1) carbonation – which is expected to produce at least partial filling of shrinkage-induced cracks – and (2) mitigation of drying shrinkage through the use of shrinkage-reducing admixture (SRA), which modifies the pore solution surface tension in concrete. Finally, the potential prospects and advantages of the SHG method using Rayleigh surface waves for the nondestructive evaluation (NDE) of concrete are discussed.

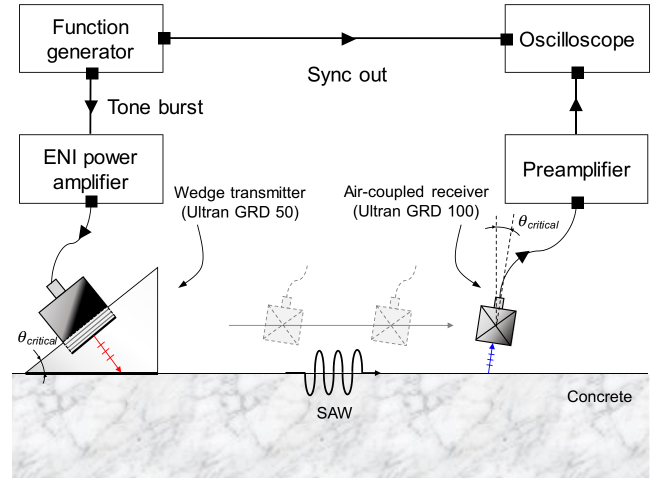

Fig. 1. Schematic of the SHG setup.

2. Materials and experiments

Two companion, long cylindrical concrete specimens of 10 × 41 cm (4 × 16 in.) were produced from ASTM C150 Type I/II Portland cement [18,19] at water-to-cement by mass ratio of 0.60, according to the mix design in Table 1: one for tracking the change in mass and the other for monitoring microstructural changes with the acoustic nonlinearity parameter.

After fogroom curing for 28 days, the fully saturated specimens were promptly moved to a drying environment (24 ± 0.1 °C and 20% RH), where changes in mass and acoustic nonlinearity parameter are assessed as a function of time. Precise control of the environmental conditions was ensured by monitoring the temperature of both the room and the specimen surface, and the SHG measurements were performed in this controlled environment. It should be noted that the specimens were not subjected to external restraint during the drying process, and exposure of the unrestrained concrete specimens to the drying environment was the driving force for any changes in the microstructure during this period.

Fig. 1 shows a schematic of the SHG measurement to detect the nonlinear Rayleigh surface waves, while Fig. 2 shows the results of the SHG measurements. The measured time domain signal and frequency spectrum using the fast Fourier transform (FFT) are shown in Fig. 2 (a) and (b) respectively. Fig. 2 (c) shows that the SHG measurements are viable in these concrete specimens, since the measured A_2 increases with increasing propagation distance, properly indicating that the measured acoustic nonlinearity is due to the material nonlinearity, while the measured A_1 decreases with propagation distance. Finally, Fig. 2 (d) shows that the measured, relative acoustic nonlinearity parameter, the slope of the linear fit for the measured A_2/A_1^2 versus propagation distance, is cumulative with propagation distance as predicted by Eq. (1). Note that the coefficient of determination (R^2) is higher than 95% for all these SHG measurements, signal averaging of 256 separate measurements is used to increase signal-to-noise ratio (SNR) and the entire measurement at each propagation distance is repeated 2–3 times. The repeated SHG measurements show that the maximum variation in the measured acoustic nonlinearity parameter is 2%. The monitoring of the mass change is performed at the same time period on the companion sample. Note that the mass measurement is performed with the scales in the drying environment and repeated 4 times for each day; the standard deviation for the mass measurement indicates that the error of each measurement is negligible (less than 0.006 kg). Moreover, it is believed that the mass change can be used as one reference to link drying shrinkage to the measured acoustic nonlinearity parameter.

Table 1
Mixture design for 1 kg/m^3 (lb/yd^3) of concrete.

Material	kg (lb.) of Material
Water	271 (365)
Cement (ASTM C150 Type I)	361 (608)
Coarse aggregate	872 (1470)
Fine aggregate	784 (1322)
Water-to-cement ratio (w/c)	0.60

3. Results and discussion

3.1. Free shrinkage and microstructural development

Fig. 3 shows the mass change (denoted by the red squares) of the specimen during the dying period from 28 to 55 days of age. It is observed that the mass monotonically decreases (from 7.120 kg to 6.942 kg), showing that the mass decreases rapidly up to 35 days of age and then the rate of change is asymptotically decreased [20,21]. This behavior can be attributed to the following sequences: (1) the low external RH (20%) facilitates an imbalanced pore pressure and the initial rate of water absorption [22,23]; (2) the relatively high w/c of 0.60 provides a sufficient interconnectivity among the pores [24]; (3) the loss of water first occurs in larger pores and is successively followed by smaller pores [22]; and (4) the tensile stresses are developed as the pores become partially emptied of water cause microcracking near the drying face [8,24].

These microcracks will eventually increase the material nonlinearity particularly near the surface, and thus the acoustic nonlinearity parameter should be able to track the formation of these microcracks, and monitor the effect of drying shrinkage. The blue circles in the Fig. 3 shows the results of the acoustic nonlinearity parameter measured with the SHG method as a function of age. As each logarithmic curve fit indicates, the trends of both the measured mass change and acoustic nonlinearity parameter follow each other. This means that the mechanical phenomena resulting from the mass reduction are readily detected with the acoustic nonlinearity parameter, β. These results show that the acoustic nonlinearity parameter increases by 218% (from 2.27×10^{-7} to 7.24×10^{-7}), while the mass has a maximum decrease of 2.5% in the period from 28 to 55 days of age. The 218% increase in β is due to the formation of microcracks as the moisture migrates near the surface, and is evidence of the high sensitivity of β to changes in the microstructure. Furthermore, the logarithmically increasing trend of the measured acoustic nonlinearity parameter is evidence of the fact that the dried surface of the specimen reaches equilibrium with the environment, and thus the tensile stresses developed relax over time [22].