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Monitoring setting and hardening of concrete by active acoustic method: Effects of water-to-cement ratio and pozzolanic materials

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HIGHLIGHTS

- An active acoustic method is used for hydration monitoring of early age concrete.
- The setting and hardening of early age concrete is a three-stage process.
- Wave velocity increases while attenuation coefficient decreases with time.
- Evolutions of wave velocity and attenuation coefficient obey cement chemistry.
- The attenuation coefficients of all concretes converge gradually to ~4 Np/m.

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ABSTRACT

An active acoustic method is used to monitor the setting and hardening of early age concrete, by recording and analyzing the wave velocity and attenuation coefficient. The effects of water-to-cement ratio and pozzolanic materials (fly ash and silica fume) are examined. The central frequency of the acoustic excitation is 6 kHz, which is much lower than that of ultrasound and can enhance the signal-to-noise ratio when applied to very early age concrete. It was found that the wave velocity measurement can reveal clearly three stages in the hydration process of early age concrete, and an aluminate hydrates phase transition period can be defined based on the attenuation coefficient measurement. Lower water-to-cement ratio and the incorporation of more silica fume facilitate a faster development of both wave velocity and attenuation coefficient, and achieve higher one-day wave velocity values, showing their accelerating effects. The incorporation of fly ash postpones the development of both wave velocity and attenuation coefficient, and achieves lower one-day wave velocity values, showing its retardation effect. The attenuation coefficients of all concretes tend to converge to the same value, i.e. 4 Np/m.

1. Introduction

Ultrasound techniques have been used for many years in concrete technology, for monitoring the early age setting and hardening of cement based materials [1–8] or the strength gain of concrete [9–11]. Ultrasound denotes a sound pressure wave with a frequency greater than 20 kHz. When used in health monitoring of hardened concrete structure, ultrasound techniques normally work very well, because the attenuation coefficient of hardened concrete is low [3,12–15]. However, for fresh or early age concrete, the attenuation coefficient is very large, and the signal-to-noise ratio decreases with increasing testing frequencies [16]. When ultrasonic method is used for early age monitoring of setting and hardening, it is sometimes difficult to distinguish the meaningful signal from the noise [3]. For the purpose of early age monitoring, a sound source with lower frequencies is more effective.

In the present study, an active acoustic method is employed to monitor the setting and hardening process of concrete. The adopted testing system is similar to that of ultrasonic P-wave transmission measurement [4], except that the central frequency is around 6 kHz, which is much lower than that of ultrasound, i.e. 20 kHz. Although most instruments for P-wave transmission measurement were designed to record several parameters other than P-wave velocity, only the P-wave velocity has been used fairly widely as an index of the hydration process [7]. Parameters such as attenuation, relative energy and frequency spectrum have not been fully utilized for analysis [1,2]. In this study, apart from the wave velocity, the attenuation coefficient is also used to characterize the changes in early age concretes. The setting and hardening processes of different concretes are examined by using the developed active acoustic method, considering the effects of water-to-cement

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ratio (w/c) and the incorporations of pozzolanic materials, i.e. silica fume and fly ash.

2. Experiments

2.1. System

A recently developed monitoring system [17] was used in the present study. The functional block diagram for the measurement system is shown in Fig. 1(a). For the early-age monitoring of concrete, a limiting stopper is employed to fix two sensors into the formwork with a determinate distance of 10 cm, before the casting of fresh concrete, as shown in Fig. 1(b). The black sensor acts as the embedded emitter for signal generation, while the white one acts as the embedded receiver to receive the transmitted signals. The sensors are 85 mm long, 45 mm wide and 110 mm high. They are fabricated through wiring and encapsulation of cement-based piezo-electric composite sensoring elements, and details of the fabrication can be found in [16,17]. Before every experiments, the sensors are set using the same limiting stopper as that used in fresh concrete, and calibrated in pure water. The formwork is made of five wooden plates, as connected by bolts. It is 400 mm long, 120 mm wide and 100 mm high. Rubber membranes of 1 mm thick are stuck on the inner sides of the formwork to mitigate noise. Both the sensor pair and the formwork are reusable after each test. In comparison with the P-wave transmission systems used by other researchers [2–4,7], the adopted system has two characteristics. First, cement-based piezoelectric composite sensors [18], rather than the common commercially available sensors, are used. The acoustic impedance of this composite is very close to that of hardened concrete, which ensures the minimum signal distortion and the maximum signal energy transmission efficiency between these two materials [18,19]. Second, a pair of sensors are embedded in the fresh concrete mixture rather than fixed on the surface of the concrete specimen. In this way, the interface-contacting problem due to concrete shrinkage can be solved, so that the method can be more easily utilized in real concrete structures [10,20,21]. These two characteristics make sure that the sensor couple can produce and detect the propagation of mechanical waves with high sensitivity [16,22].

2.2. Parameter acquisition

2.2.1. Wave velocity

As the distance between the signal emitter and receiver is fixed, the wave velocity in the monitored concrete can be easily calculated if the wave traveling time is known. After calibrated in pure water, the system will automatically calculate and record the traveling time as

$$\Delta T = T_{\text{concrete}} - \left(T_{\text{water}} - \frac{S}{V_{\text{water}}}\right) \tag{1}$$

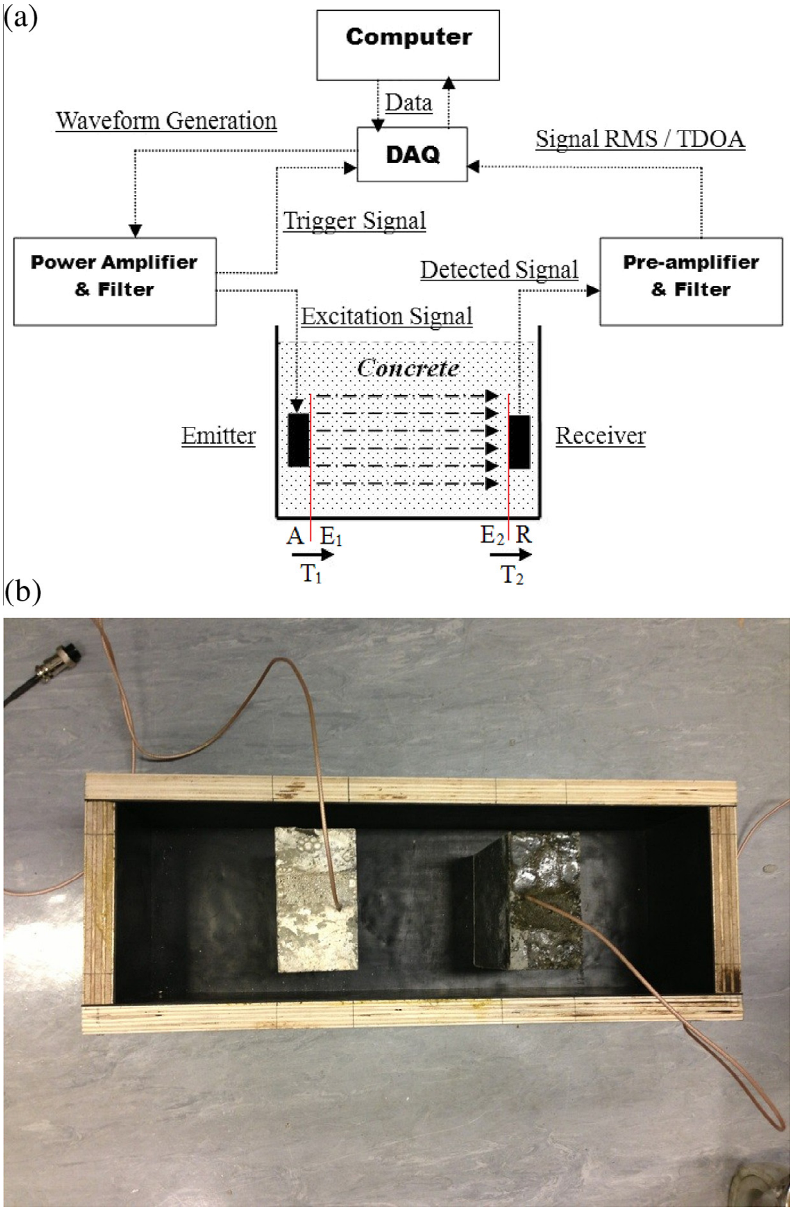

Fig. 1. Hydration monitoring system: (a) block diagram; (b) sensors and formwork.