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Effects of air voids on ultrasonic wave propagation in early age cement pastes

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ABSTRACT

The objective of this paper is to investigate effects of air voids on ultrasonic wave propagation in fresh cement pastes, and relate ultrasonic wave parameters to cement setting times. First, Biot's theory was used to analyze wave propagation in poroelastic media containing air bubbles. Then, in the experimental study, both the compressional (P) and shear (S) waves were monitored in cement pastes with different water/cement ratios (w/c = 0.4 and 0.5) and various air void content (0.1%–5.3% by cement paste volume). Experimental results indicated that existence of air bubbles in cement paste significantly decreases the P wave velocity, but has little effect on the shear wave propagation. Further analysis shows that the shear wave velocity corresponding to the Vicat initial setting times is a relatively constant value for the investigated air content range. This study shows the potential of using shear waves to monitor setting and hardening process of cement.

1. Introduction

Many test methods have been developed to characterize early age properties of cementitious materials, which include Vicat needle [1], rheological measurement [2], chemical shrinkage [3], electrical conductivity [4] and ultrasonic methods [5–10], etc. These methods measure mechanical, chemical and electrical properties during stiffening and hardening processes of cementitious materials. However, the microstructural development and fluid-to-solid transition, or the solidification process, will be better described by methods that measure mechanical properties of cementitious materials.

Ultrasonic waves have been widely used to characterize and evaluate hardened concrete based on the relationship between wave velocity and the mechanical properties (Young's modulus) of elastic solids. Since 1980s, research using ultrasonic waves to investigate early age properties of cement pastes and concrete has grown rapidly. Elastic and viscoelastic properties of cementitious materials can be obtained from ultrasonic wave velocity [3–6,11–13], attenuation [4] or reflection [9] measurements.

In 1980s, Keating et al. [6] investigated ultrasonic longitudinal (P) wave propagation in fresh cement pastes. They showed that at very early age, the P wave velocity V_P is governed by the fluid phase before the solid phase becomes interconnected. They also found that presence of air bubbles strongly influences the P wave velocity and attenuation. Sayers and Dahlin [12] confirmed the findings by comparing ultrasonic wave signals in de-aired and as-mixed cement pastes, and used Biot's theory to analyze wave propagation in saturated porous media. Since then, many studies have been focused on correlating the P wave velocity V_P and the Vicat initial setting time [7,13–17]. Researchers have developed different methods to identify initial setting time of cementitious materials based on certain features on the ultrasonic velocity curves. Those features include the point where V_P starts to increase [7,11,13], the inflection point on velocity curve [17], or when V_P reaches the velocity in water [18]. To eliminate influence of air voids, some researchers used de-aired cement samples, and defined the setting point as the time when velocity starts to increase in de-aired samples [6,8,12,19]. However contradictory conclusions often result since some methods give very different setting time. It is still unclear how to determine the setting time based on P wave velocity measurement.

Although ultrasonic measurements obtained from de-aired cement samples show good correlation between P wave velocity and the setting time, using de-aired sample is unrealistic in field testing. On the other hand, quantitative study about effects of air voids on ultrasonic waves has been very limited. Recently, Kmack [20] experimentally investigated the effects of air voids on ultrasonic P wave propagation in fresh cement pastes by introducing various amount of air-entraining agent (AEA), 0–0.6% by weigh of cement. Kmack found that ultrasonic waves in air-entrained specimens showed significantly lower wave velocity and signal amplitude at early ages than the non-air-entrained specimens.

Shear waves have also been examined for monitoring setting and hardening of fresh cement pastes. Because shear waves have very low velocity and high attenuation in fluid cement paste, with the transmission setup, shear waves could only be detected a few hours after mixing. D'Angelo et al. [5] showed that shear waves are more

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