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Using the ultrasonic wave transmission method to study the setting behavior of foamed concrete

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HIGHLIGHTS

- The setting behavior of FC was monitored by ultrasonic transmission method.
- Wave propagation and attenuation were modeled by Anderson and Hampton's theory.
- Certain ranges of UPV were suggested for estimation of the setting times of FC.
- The bubble instability mechanism in FC was also discussed.

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ABSTRACT

The objective of this paper is to investigate the possibility of using ultrasonic wave transmission method to study the setting behavior of foamed concretes (FC), and relate ultrasonic wave parameters to foamed concrete setting times. First, Anderson and Hampton's theory was used to analyze wave propagation and attenuation in poroelastic media containing considerable air bubbles characterized by 3D X-ray computed tomography (XCT). Then, the compressional (*P*) waves were used to automatically and continuously measure the FC pastes with different plastic density (300, 500, 800 and 1000 kg/m^3) and different fly ash contents (20%, 40% and 60% by weight of cement). The influence of curing temperatures (20, 40, 60 and 80 °C) was also studied. Experimental and theoretical results indicated that the presence of air bubbles in cement paste significantly decreases the ultrasonic *P* wave velocity (UPV). Three characteristic stages can be identified during the setting process of an arbitrary FC paste: dormant stage, acceleration stage, and deceleration stage. Besides, a stepwise increase of the wet density results in shorter dormant stage, acceleration stage and larger final UPV. Hydration reaction rate is obviously promoted with an increase in curing temperature, while the reverse phenomenon is observed when fly ash is incorporated. Further analysis shows that the *P* wave velocity corresponding to the Vicat initial and final setting times is a relatively constant value with reasonable widths for the investigated density range. Finally, the corresponding ranges of UPV were given for setting time estimation in practical application.

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1. Introduction

Foamed concrete (FC) is a type of lightweight insulation material consisting of Portland cement paste or cement filler matrix (mortar), in which a homogeneous air-void or pore structure are created by introducing suitable air foaming agent [1–3]. Foamed concrete can be designed to have any density within the range of 400–1600 kg/m^3, which possesses self-compacting, light weight, low strength (1–10 MPa) and excellent thermal insulation properties, suitable for application to partition, insulation and filling grades [4,5]. Compared with other lightweight concretes, foamed concrete has the following merits: it is expected that construction elements in foamed concrete can be fabricated on construction site. This is an important advantage with respect to other insulation materials such as autoclaved cellular concrete, whose preparation process is rather complex and energy consuming. In addition, it is possible to design the properties of foamed concrete according to practical requirement by varying material parameters such as cement paste composition, foam size and volume fraction.

Early hydration process and micro-structural formation at early ages are of great importance for FC, since it directly influences the physical, mechanical and functional characteristics of the matured FC. Although several documents discussing the evolution of hydration heat in foamed concrete have been published [6,7], there is still a lack of information revealing the mechanical parameters during early age setting process or estimating the setting time of

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Nomenclature

α	acoustic attenuation coefficient in gassy sediment, dB m^{-1}
γ	ratio of the specific heat capacity of air at constant pressure to that at constant volume
δ_G	shear modulus loss factor
ρ	density of foamed concrete paste, kg m^{-3}
ρ_g	density of air, kg m^{-3}
ρ_w	density of water, kg m^{-3}
ω_0	angular resonance frequency, rad s^{-1}
ω	angular frequency, rad s^{-1}
α_s	see Eq. (A3)
A	gas polytropic coefficient
b	binder content, kg
B	see Eq. (A16)
c	cement content, kg
C_g	thermal conductivity of gas, J s^{-1} m^{-1} $°C^{-1}$
d	bubble damping
d_*	see Eq. (A8)
d_f	bubble damping due to fluid viscosity
d_r	bubble damping due to radiation
d_t	bubble damping due to thermal properties of gas
D	target density, kg m^{-3}
f	frequency of acoustic signal, Hz
f_0	resonance frequency, Hz
f_*	see Eq. (A13)
f_a	fly ash content, kg
G	dynamic shear modulus of nongassy cement paste (host material), Pa
G'	imaginary part of complex shear modulus, Pa
i, M	index terms in Eqs. (A6) and (A7)
k	acoustic wave number in bubble-free cement paste
K	bulk modulus of nongassy cement paste, Pa
K_f	bulk modulus of framework, Pa
K_s	bulk modulus of mineral grains, Pa
K_w	bulk modulus of pore water, Pa
L	length of the container, m
n	sediment porosity, fractional
n_g	gas content, fractional
P_0	ambient hydrostatic pressure, Pa
r	bubble radius, m
r_0	equilibrium bubble radius, m
s_p	specific heat of gas at constant pressure, J kg^{-1} $°C^{-1}$
t	pulse travel time, s
V	acoustic phase velocity in foamed concrete, m s^{-1}
V_0	acoustic phase velocity in nongassy cement paste, m s^{-1}
V_p	compressional wave velocity of foamed concrete, m s^{-1}
V_{foam}	foam volume, l
W	water content, kg
X	see Eq. (A17)
X_*,Y_*	frequency-dependent variables incorporating gas fraction and damping for a single gas bubble size
X_1,Y_1	frequency-dependent variables incorporating gas fraction and damping for a distribution of gas bubble sizes, which may be expressed as a histogram

foam concrete, which is a important parameter for practical application. Furthermore, it should be noted that the setting behavior of foamed concrete also affect its stability [8]. Initially, the self-weight of foamed concrete is carried by the surface tension in the bubbles and as long as this remains the mix will be stable. However, foams can only retain their surface tension for a specific period after which it reduces, the bubbles consequently get bigger and combine with adjacent bubbles and burst. However, at some point the initial set of the cement will occur and the liquid porous media becomes a poroelastic media. At this point the self-weight can be hold by the solid framework composed of unhydrated cement and hydration products and not the bubbles. Thus, there is a critical point for any mix at which time initial set must occur, otherwise the mix will inevitably become unstable.

For the measurement of the hydration of cement and concrete, during the recent years, ultrasonic methods have been applied successfully. This method has the advantages over the more traditional methods, such as Vicat needle test, scanning electron microscope (SEM) and infrared radiation test (IR), that ultrasonic methods are continuous and non-destructive, and that they can provide information about the microstructure development and the related mechanical properties like strength development based on the relationship between wave velocity and the Young's modulus of elastic solids. These elastic properties of cementitious materials can be obtained from ultrasonic wave velocity [9–17], attenuation [18] or reflection measurement [19,20].

In 1980s, Keating et al. [12] firstly applied the ultrasonic wave propagation method to study the time evolving properties of cement pastes. They showed that initial longitudinal pulse velocity V_p is governed by the fluid phase until the time at which the solid phase becomes interconnected. They also found that the presence of air bubbles trapped in the paste strongly affects the P wave velocity and attenuation. Sayers and Dahlin [14] confirmed the findings by comparing ultrasonic wave signals in de-aerated and as-mixed cement pastes and used Harker and Temple theory [21] and Biot's theory [22,23] to study the acoustic response in cement suspensions and porous elastic cement paste, respectively. Recently, a number of studies have also been focused on correlating the certain features on the ultrasonic velocity curves (the inflection point on V_p curve [24]; the point where V_p begins to increase [13,15,25], or when V_p and V_s reach the range of certain value [26] and the point where V_p has maximum changing rate [16,17]) and the setting time.

To study the effect of bubbles on the acoustic response of porous elastic media, there are a number of literatures and much of the researches up to 1980 were summarized in two papers by Anderson and Hampton [27,28]. From their discussion and from more recent studies [29,30] it is clear that models of ultrasonic behavior in gassy media depend on the relationship between particle and bubble size. If the bubbles are small relative to particle size (the air content is small, such as cement paste with AEA), they remain within the pore fluid and behave as small bubbles in water. In this instance, acoustic propagation is primarily affected by changes in the fluid-air compressibility [31]. If, on the other hand, bubbles are large relative to particle size (such as foam concrete) the structure of the solid frame interacts with the bubbles and changes both bubble compressibility and resonance [27–30].

The objectives of this study are to examine the effectiveness of advanced ultrasonic techniques to monitor the setting behavior of foamed concrete. This method and equipment have already proven to be reliable for characterizing the setting behavior of normal and high-performance cement pastes [16,17]. First, the effects of air voids on ultrasonic wave velocity were theoretically investigated based on Anderson and Hampton's theory for poroelastic media. Then, in the experimental study, a direct ultrasonic transmission measurements are performed on a set of foamed concrete pastes

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