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Elastic wave characterization of controlled low-strength material using embedded piezoelectric transducers

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HIGHLIGHTS

- Embedded piezoelectric transducers were used to monitor hydration process of CLSM.
- Piezoelectric disk elements generate compressional waves.
- Bender elements generate shear waves.
- The shear wave velocity varies according to the elapsed time as a power function.
- High water content in CLSM hinders interconnection of cementitious particles.

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ABSTRACT

Ultrasonic wave methods have been widely used to monitor the hydration process of cementitious materials. However, the conventional ultrasonic wave methods require a coupling agent and pressure or a buffer material to maximize the coupling of the transducer. The objective of this study is to apply two types of embedded piezoelectric transducers to controlled low-strength material (CLSM) and to monitor the elastic wave characteristics during the hydration process. The CLSM mixture is composed of silica sand, calcium sulfoaluminate cement, fly ash, and water, and then, the CLSM mixture is prepared with three different fine contents. Using piezoelectric disk and bender elements installed in cuboid containers, the compressional and shear waves are measured for 72 h at various intervals. The monitoring results show that during the hydration process, the evolution of shear wave velocities obtained using the bender element is less variable than that in compressional wave velocities obtained using the piezoelectric disk element. As a power function, the shear wave velocities increase with an increase in the elapsed time. As the fine content of the CLSM mixture increases, the water content required for the flowability of the CLSM mixture increases and the shear wave velocities then decrease. The results demonstrate that the CLSM mixture with high water content induces a delay of the interconnection of the cementitious particles at the very early stage of the hydration. The geometric boundary condition of the container is considered as an aspect of the estimation of the shear wave velocity obtained by the bender element. This study demonstrates that the embedded elastic wave transducers can be effectively used for monitoring the hydration process of CLSMs.

1. Introduction

Controlled low-strength material (CLSM), a cementitious material, is used for backfill, structural fill, and road construction. For the backfill of narrow trenches, some characteristics of CLSM, such as flowability, self-compaction, and durability, are superior to those of conventional compacted granular material. In the case of temporary construction, the low compressive strength of the CLSM is required for future excavation. Furthermore, early age strength development is desired for fast restoration of the excavated trench [1]. To characterize the early age properties of cementitious material, the setting and hardening times are conventionally measured using the penetration resistance method [2]. However, the penetration resistance method is a destructive testing method and impractical for continuous monitoring of the early age properties of cementitious material.

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For monitoring of the early age properties of cementitious material, various testing methods based on ultrasonic waves have been studied, which can be divided into two groups: ultrasonic wave reflection (UWR) and ultrasonic pulse velocity (UPV). The principle of the UWR method is related to wave reflection phenomena at the interface between a specimen and a buffer. The buffer between the specimen and wave transducer is necessary for remaining in contact when the specimen is still in a fluid state. A variety of buffer materials, such as Plexiglas, steel, and acrylic glass, have been used to improve the sensitivity of the UWR method [3–6]. The UWR method, which allows access to only one side of a specimen, has the advantage of in-situ assessment of the early age properties of cementitious material. However, the UWR method only offers local characterization around the interface between the buffer and the specimen. In contrast, the UPV method can provide an estimation of the material properties within the region between two transducers, and the wave velocities estimated from the UPV method are directly related to the dynamic modulus of elasticity. However, to maximize the coupling, adequate pressure should be applied to the transducers, and a coupling agent needs to be used to minimize the effect of the presence of air at the interface between the transducer and the specimen.

To overcome the limits of the UPV and UWR methods, an embedded piezoelectric transducer was introduced by Gu et al. [7]. The low cost of an embedded piezoelectric transducer facilitates in-situ monitoring of the cementitious material, and embedding such transducers enables continuous wave characterization without any pressure or agent applied for the coupling. The embedded piezoelectric transducers were developed to monitor the compressional waves during the hydration process of cement paste and concrete [8,9]. Furthermore, the embedded piezoelectric transducers were applied for crack detection and health monitoring of the concrete structures [10,11]. As a shear wave transducer, the bender element, which has been widely used in geotechnical engineering, was applied to monitor the setting and hardening processes of mortar and concrete [12,13]. However, the application of embedded wave transducers to the cementitious material has several difficulties, and signal interpretation related to the transducers is needed.

This paper presents the application of two types of embedded piezoelectric transducers for monitoring the hydration process of the CLSM with consideration of the wave characteristics. First, the components and properties of the CLSM are introduced. The embedded piezoelectric transducers and test setup for wave measurement are demonstrated. The signals obtained from the transducers are analyzed in both time and frequency domains. Compressional and shear wave velocities, connectivity of particles and boundary effects are discussed.

2. Experimental studies

2.1. Materials

The CLSM mixture used in this study contains sand, silt, calcium sulfoaluminate (CSA) cement, fly ash, and water. Recently, with the growing interest in sustainability, native soils have been used as a substitute for conventional fine aggregate in CLSM [14–16]. Accordingly, two types of soils with different particle sizes were used as fine aggregate, considering the various grain size distributions of the native soil used in the CLSM mixture. The sands with a median diameter (D_{50}) of 0.59 mm and the silts with a median diameter (D_{50}) of 0.02 mm were used. The gradation properties for the fine aggregates are summarized in Table 1. CSA cement and fly ash were used as binders in the CLSM mixture. The small spherical particles of the fly ash ameliorate the flowability of the CLSM mixture, preventing segregation. However, with a large amount of fly ash, the mixture slowly reaches the early-strength required for the rapid restoration of the excavated ground. Thus, CSA cement comprising ordinary Portland cement and calcium sulfoaluminate-based expansive admixture at a 9:1 ratio was added in order to catalyze the hydration reaction and rapidly gain the strength at an early stage. The fly ash mainly contained 40.8% calcium oxide (CaO), 20.4% silica (SiO_2), 11.4% aluminum oxide (Al_2O_3), and 9.2% Iron (III) oxide (Fe_2O_3) with other minor components. In addition, an alkali-free setting accelerator was used to reduce the setting time of the mixture.

2.2. Specimen preparation and properties

Using the components mentioned in previous section, three different CLSM specimens were mixed as presented in Table 2. In the specimens, the ratio of fly ash: cement: fine aggregate was fixed at 1: 0.3: 7, within the typical range of mixture proportions [17]. To investigate the gradation effect of fine aggregate, the relative weight of silt to total aggregate (fines content, FC) was changed to 10%, 50%, and 90%. Under dry conditions, the fly ash, CSA cement, and aggregates were first mixed for three minutes, and the water and accelerator were then added in sequence. A certain amount of water was set to ensure each CLSM specimen was more flowable than a 200 mm flow. For the flowability measurement of the CLSM mixture, flow tests were performed according to ASTM D6103 [18]. CLSM specimens cured in cylindrical molds of 5 cm in diameter and 10 cm in height were used to evaluate the mechanical properties of the specimens. At 28 days after curing, the compressive strength and bulk density of the specimens were measured, as summarized in Table 3. According to the definition by the American Concrete Institute committee 229 [19], the compressive strength of CLSM at 28 days should be less than 8.3 MPa, and in most cases, a

Table 1
Grading properties for fine aggregate.

Type	*D_{10} [mm]	*D_{30} [mm]	*D_{60} [mm]	Gradation coefficient C_c	Uniformity coefficient C_u
Silt	0.004	0.011	0.025	1.11	5.95
Sand	0.36	0.48	0.64	1.00	1.75

* The D means the grain diameter and its subscript number indicates percent finer than the grain diameter.

Table 2
Mixed proportion by weight for CLSM.

Fine content [%]	Fly ash	CSA cement	Sand	Silt	Water	Accelerator	w/c	w/b
10	1	0.3	6.3	0.7	2.05	0.018	6.8	1.6
50	1	0.3	3.5	3.5	2.45	0.018	8.2	1.9
90	1	0.3	0.7	6.3	3.6	0.018	12	2.8