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Utilization of by-product in controlled low-strength material for geothermal systems: Engineering performances, environmental impact, and cost analysis

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ABSTRACT

This paper evaluates the feasibility of by-product-based controlled low-strength material (CLSM) as a grout for geothermal systems. Quartz-based mine tailings and pond ash were adopted as filler and fine aggregates, respectively. Settlement, compressive strength, and thermal conductivity, required for grout for geothermal systems were investigated and the leaching behavior of toxic elements from the CLSM was evaluated. In addition, a cost analysis for actual construction sites of the geothermal system was conducted using a design program. The high-workable CLSM with tailings and pond ash satisfied the strength specified in the ACI 229R and its thermal conductivity was higher than that of conventional grout, i.e., bentonite-sand mixture. The CLSM made only with tailings satisfied the 'Treatment Standard for Hazardous Wastes' in the Code of Federal Regulations of US governments (40 CFR 268.40), whereas that with both tailings and pond ash did not. The total construction costs of the geothermal system reduced up to 20.8% when utilizing the by-product-based CLSM compared with conventional grout.

1. Introduction

Controlled low-strength material (CLSM), also known as flowable fill, is a type of cementitious fill with self-compacting properties and low strength for re-excavation (Katz and Kovler, 2004). Conventional cement mortar has strength greater than 20 MPa, whereas the required range of compressive strength of CLSM is 0.3–2.1 MPa, or 8.3 MPa, which varies according to the likelihood of re-excavation (ACI 229R, 1999). The required amounts of cement and cementitious binder are significantly lower than that for conventional mortar owing to its low strength. The CLSM can be applied as filler for sites where external compaction cannot be applied. From the standpoints of environment and cost, many types of by-products have been utilized as fillers and binders for CLSM. For example, the use of fly ash and bottom ash from coal thermal power plants is specified in the standard recipes for the CLSM for numerous states in the USA (ACI 229R, 1999). Moreover, numerous studies have been conducted regarding the adoption of other by-products, such as quarry fines, waste gypsum, and excavated soil in CLSM (Taha et al., 2007; Finney et al., 2008; Naganathan et al., 2012). There are many advantages to applying the by-products in cement-based composites, including CLSM and concrete; these include the reduction in leaching potential of toxic elements from by-products, mass consumption of by-products, conservation of natural resources, and cost reduction (Nataraja and Nalanda, 2008).

Previous studies show that pond ash and mine tailings may be used as fillers for CLSM (Kim et al., 2016a, 2016b). Pond ash, which is a coal ash that has been disposed to a pond, has unique characteristics, such as rough surface texture, wide particle size gradation, high content of unburned carbon and organic impurities, and in some cases, high chloride content, which hinders the utilization in structural concretes (Fall et al., 2008). However, these characteristics are negligible for the utilization in CLSM, and even improve the strength of CLSM owing to the pozzolanic reaction (Naik et al., 2003).

Mine tailings, which are mineral residues after the extraction of the target elements from ores, are also not applied in structural concrete because of their particle size (Thomas et al., 2013).

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Generally, the tailings with a similar particle size gradation to cement tend to block the inter-connection of hydration products, and this leads to a decrease in concrete strength (Choi et al., 2009). However, in the case of CLSM, the required strength was not so high that this could be utilized without difficulties. It was reported that the performances of CLSM containing pond ash or tailings could satisfy the guidelines stipulated in American Concrete Institute Committee Report 299 (ACI 229R, 1999), i.e., flowability and uniaxial compressive strength higher than 200 mm and 0.3 MPa, respectively (Kim et al., 2016a). Moreover, the leachabilities of heavy metals and arsenic from the CLSM with the tailings, which were measured with Toxicity characteristic leaching procedure (TCLP) tests in accordance with the US EPA Method 1311, were lower than the limitations specified in the Code of Federal Regulations of US Governments (40 CFR 268.40) (Kim et al., 2016a).

These CLSMs containing by-products could be applied as a grout for geothermal systems (ground-source heat-pump systems). Of the various types of geothermal systems, a closed-loop vertical-type system is widely applied owing to its high energy exchange efficiency (Lund et al., 2004). The grout is the part of the system that fills the spaces between boreholes and pipes for liquid heat exchangers. If fresh grout has excellent workability, it can fill the boreholes without voids or gaps, leading to an enhancement in energy exchange efficiency of the system (Philippacopoulos and Berndt, 2001). Compared with conventional grout materials, such as bentonite-silica sand mixtures and cement mortar, the CLSMs have higher workability and self-compacting properties. This material fills the holes compactly, resulting in a narrow and complicated cross-section, without the application of high-pressure injection or external vibration. Moreover, the cementitious binder-based grout is required where chloride penetration of grout may lead to harmful effects on plant availability (Weggler et al., 2004)

Quartz-based mine tailings can improve the thermal conductivity of CLSM. Note that the mineralogy of the quartz-based tailings was identical to that of the silica sand, which has been used as grout for geothermal systems owing to its higher thermal conductivity compared with other minerals such as calcite (Clauser and Huenges, 1995; Kim et al., 2016a). If the thermal conductivity of the grout improved, the length of the pipe required to exchange the heat between the heat exchanger and the ground can be shortened, and thus the cost of boring can be reduced (Allan and Kavanaugh, 1999). Moreover, owing to the pozzolanic properties, the addition of pond ash can decrease the required cement content to obtain equivalent strength of the mixtures. If the cement content decreased, the pH of the ground water would increase, i.e., the water contamination can be controlled.

In the present study, the feasibility of by-product–based CLSM as a grout for geothermal systems was evaluated. Quartz-based mine tailings and pond ash were adopted as the filler and fine aggregate, respectively, in the CLSM. Mix proportions were designed to satisfy target flowability. Various engineering properties required for grout for geothermal systems, including settlement, compressive strength, and thermal conductivity, were investigated. The leaching behavior of toxic elements from the CLSM was evaluated by two different test methods; TCLP test and tank leaching test. In addition, to investigate the economic benefits of the application of by-product–based CLSM, a cost analysis for actual construction sites of the geothermal system in South Korea was conducted using a geothermal system design program known as Ground Loop Design (GLD) software (Gaia Geothermal, 2012).

Table 2
Physical properties of powders.

Properties	Mine tailings	Pond ash	Natural sand
Specific gravity	2.62	2.15	2.60
Water absorption (%)	–	4.65	0.83
Fineness modulus (F.M.)	–	3.48	2.60
D10 (μm)	1.8	110	150
D50 (μm)	5.6	1060	710
D90 (μm)	43.67	5200	2500

2. Materials and methods

2.1. Materials

The mechanical and chemical properties, crystalline structures, and particle shape and size gradation of the materials used are presented in Tables 1 and 2 and Figs. 1–3. Note that the crystalline structures and the chemical composition of the powders shown in Fig. 1 and Table 1 were measured by an X-ray diffractometer (XRD; X'Pert^3 Pro MRD, PANalytical, Netherlands) and X-ray fluorescence spectrometer (XRF; RIX2000, Rigaku Inc., Japan), respectively. The particle morphologies and their size gradations were observed by a scanning electron microscope (SEM; MIRA 3 LMU, Tescan Orsay Holding) and a laser particle size analyzer (Helium–Neon Laser Optical System, HELOS R1, Sympatec GmbH, Germany), respectively. Heavy metals in the powders were extracted using an aqua regia digestion and the concentrations thereof, shown in Table 3, were obtained using atomic absorption spectrophotometry (AAS; AA-7000, Shimadzu, Japan). The details of the experimental process are listed in Kim et al. (2016a).

The mine tailings were sourced from a tailing dam at the Sun-shin mining site, a gold mine located in the Jollanamdo province of South Korea, approximately 340 km south of the capital city Seoul (capital). Note that the tailing management for the Sun-shin mine site is highly important because of the following reasons: 1) the mine is in operation, and thus the tailings are produced continuously, 2) the mine site and the tailing dam are located on the seashore (less than 1 km from the sea), and thus the leaching of toxic elements should be prevented. As shown in Table 1 and Fig. 1, the main composition of the tailings is quartz, and other crystals such as biotite and muscovite are contained in limited amounts. The particles of the tailings have a platelet shape owing to the biotite and muscovite crystals, which tend to be broken into thin plates (Fig. 2). The particles of the tailings were smaller than that of the cement (Fig. 3).

The pond ash was sourced from an ash pond of the Yeosu coal power plant in the Jollanamdo province of South Korea. Bituminous coal was used and the ash was discharged from the boilers to the pond as slurry, i.e., wet removal system using seawater. Recycling the of the plant pond ash is an urgent issue as the existing pond reached its capacity. The pond ash consisted of amorphous silica and aluminosilicate, and the calcium content was negligible, i.e.,

Table 1
Chemical composition of mine tailings and pond ash.

Sample	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	MnO	Na_2O	K_2O	TiO_2	P_2O_5	Loss of ignition (LOI)
Mine tailings	79.53	9.52	3.22	0.16	0.64	0.51	0.72	3.24	0.52	0.06	2.46
Pond ash	62.53	20.91	8.70	1.80	0.69	0.09	0.39	1.44	1.26	–	1.85