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Experimental and numerical investigation of thermal properties of cement-based grouts used for vertical ground heat exchanger

Daehoon Kim, Gyoungman Kim, Donghui Kim, Hwanjo Baek*

Department of Energy and Resources Engineering, Kangwon National University, Chuncheon, South Korea

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ABSTRACT

In this study, the thermal conductivities and specific heat capacities of cement-based grouts used for vertical ground heat exchanger (GHE) were investigated in a laboratory experiment. Nine different mix proportions with different water/cement and silica sand/cement ratios were scrutinized. Comparing the dried condition with the saturated condition, the specimens' thermal conductivity and specific heat capacity decreased. As the sand/cement (s/c) ratio increased and water/cement (w/c) ratio decreased, under the saturated condition the thermal conductivities of the specimens increased, whereas the specific heat capacities decreased. However, increasing s/c ratio had greater influence on the thermal conductivity improvement of the cement-based grouts than did decreasing w/c ratio. Also, due to the effect of the water's high specific heat capacity, the higher the water absorption rate of the cement-based grout was, the higher the specific heat capacity was. Additionally, in order to evaluate the effects of the thermal properties of the cement-based grouts on GHE performance, a series of numerical simulations were carried out. In the results, in the continuous operation mode, only thermal conductivity of the grout material had a positive effect on the GHE performance, whereas in the intermittent operation mode, both thermal conductivity and specific heat capacity did. This result indicates that in order to further improve GHE performance, further research related to the thermal properties of grout material will have to consider not only its high thermal conductivity but also its high specific heat capacity. The experimental and numerical results obtained in this study will prove constructive to subsequent GHE performance improvement efforts.

1. Introduction

Nowadays, due to the exhaustion of fossil fuel sources and the requirement for the reduction of greenhouse gas emissions, interest in new and renewable energy sources has increased throughout the world. Among the various new and renewable energy sources currently available, the ground source heat pump (GSHP) system is the most energy efficient, environmentally clean and cost-effective space heating and cooling system [1]. The GSHP system uses the ground as a heat source for space heating in the winter, or as a heat sink for space cooling in the summer [2]. The typical GSHP system consists of a heat pump coupled with a ground heat exchanger (GHE) wherein a working fluid exchanges heat with the ground. The GHE is classified into horizontal and vertical types according to the installation method. The vertical GHE, which usually offers higher energy performance than the horizontal type, is utilized widely in Korea [3,4]. In installing the vertical GHE, a borehole with a diameter of 0.1–0.3 m and a common depth of 50–200 m is drilled into the ground [5], the U-tube HDPE pipe is placed in position, and the borehole is filled with grout materials. The grout materials should satisfy the following conditions: (1) high thermal conductivity for efficient heat transfer between the GHE and the surrounding ground, (2) low hydraulic conductivity for control of groundwater movement and prevention of contamination of water supply and of hydraulic short circuit of different groundwater layers, and (3) high workability for ease of injection into the borehole [6,7].

Typical grout materials for the vertical GHE are bentonite and cement. However, pure bentonite and cement grouts have relatively low thermal conductivity [8]. Therefore, various experimental studies have been carried out to improve thermal conductivity, specifically by mixing grout materials with certain higher-thermal-conductivity additives. Lee et al. [9] investigated

* Corresponding author.
E-mail address: hwanjo@kangwon.ac.kr (H. Baek).

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the thermal conductivity and viscosity of seven different bentonite grouts enhanced by addition of silica sand or graphite. Delaleux et al. [10] evaluated the thermal conductivity of bentonite-graphite grouts elaborated with different forms of graphite. Allan [8] and Park et al. [11] examined the thermal conductivity of cement grout specimens (with various mixture designs enhanced by addition of silica sand), their mechanical properties and permeability in a series of laboratory experiments.

Numerical modeling has been widely employed for consideration of complex problems; indeed, it has been used in many studies to predict the performance of GSHP system. It is particularly useful in obtaining optimum designs and assessing economic feasibility prior to GSHP system installation, which incurs high initial costs due to the requirement of additional borehole drilling. Esen et al. [12] developed a 2D finite element model to simulate the temperature distribution in boreholes in soil surrounding a vertical GHE operating in both cooling and heating modes. Lee [13] developed a modified model for a vertical GHE borefield of GSHP systems based on a 3D finite difference scheme that could account for multiple ground layers in the soil. Chena et al. [14] simulated the thermal performance of a vertical GHE with a 3D finite element model, considered the different initial soil temperatures and thermal properties at different depths. Pu et al. [15] numerically investigated the effects of the Reynolds number, tube diameter and tube connection configurations on the thermal and pressure performances of a vertical GHE.

When a numerical simulation to assess the performance of vertical GHE is conducted, not only the thermal conductivity of the grout material but also the specific heat capacity is an essential parameter. Therefore, in order to accurately evaluate the performance of the GHE on the thermal properties of the grout materials through the numerical simulation, not only the thermal conductivity of the grout material but also the specific heat capacity needs to be investigated and applied to the numerical simulation. However, the previous experimental studies [8–11] have focused primarily on measurement and improvement of the thermal conductivity of grout material; the specific heat capacity has been mostly ignored.

In the present study, the thermal conductivity and specific heat capacity of cement-based grouts with varying mix proportions were investigated. Additionally, a series of numerical simulations were carried out in order to evaluate the effects of the thermal properties of the cement-based grouts on vertical GHE performance in the continuous and intermittent operation modes.

2. Materials and methods

2.1. Materials and mix proportions

The cement used in this study was ordinary Portland cement (ASTM Type I), the chemical composition of which is listed in Table 1. The additive used to improve the thermal conductivity was silica sand, the physical properties of which are listed in Table 2. According to previous studies [8,11], when the additive is sand, the amount of water is small, and as the amount of sand increases, the thermal conductivity of cement-based grout increases. Therefore, in this study, in order to investigate the thermal conductivities and particularly specific heat capacities of cement-based grouts with different water/cement ratios and different silica sand/cement ratios, nine different mix proportions were selected (Table 3). Also, for each mix proportion, three cylindrical specimens of NX-size (5 cm dia. × 10 cm height) were prepared.

Table 1
Chemical composition of ordinary Portland cement [16].

	SiO_2	Al_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	Fe_2O_3
Weight percentage (wt%)	19.8	4.5	61.8	3.5	2.6	1.2	0.3	3.2

Table 2
Physical properties of silica sand.

Particle diameter D_{10} (mm)	0.35
Particle diameter D_{60} (mm)	0.57
Uniformity coefficient (C_u)	1.63
Coefficient of curvature (C_c)	1.02
Specific gravity	2.63

2.2. Measurement of thermal properties

Thermal conductivity is the ability of a material to transfer heat, and specific heat capacity represents the capability to store heat. Specific heat capacity is related to volumetric heat capacity and bulk density, and can be calculated as

$$c_m = \frac{c_v}{\rho} \tag{1}$$

where c_m is the specific heat capacity (J/kg·K), c_v is the volumetric heat capacity (J/m^3·K) and ρ is the bulk density (kg/m^3) [17].

In this study, KD2 PRO (DECAGON Manufacturing Co., Ltd.), a handheld device, was used to measure the cement-based grout specimens' thermal properties (Fig. 1 (a)). Consisting of a controller and sensors that can be inserted into a medium, it uses the transient line heat source methods to measure the medium's thermal properties. The single-needle sensors measure thermal conductivity and its reciprocal, resistivity, while the dual-needle sensor measures thermal conductivity, volumetric heat capacity, resistivity and diffusivity [18]. Therefore, the dual-needle sensor, SH-1 (Fig. 1 (b)), was used, the specifications of which are listed in Table 4.

The SH-1 sensor takes accurate measurements in rock and cured concrete (Table 4), but it is very difficult to drill small diameter, parallel holes in these materials to accommodate the SH-1 needles. Therefore, pilot holes were molded in wet cement grout mix using the individual manufacturing pilot pins according to the following procedure: vaseline is applied to the pilot pins; the pins are installed at the top center of each specimen while it is wet; the pins are removed after 24 h curing of the specimen at room temperature. Subsequently, the specimens were cured in air (23 ± 2 °C, 45 ± 10% R.H.) over the course of 28 days.

In order to measure the bulk densities, porosities, water absorption rates and thermal properties, after the cured specimens were oven-dried at 105 ± 2 °C for 1 day, their dry unit weights were

Table 3
Mix proportions for test specimens.

Specimen no.	Water/Cement ratio	Sand/Cement ratio
SC1-1	0.3	0
SC1-2		0.5
SC1-3		1
SC2-1	0.4	0
SC2-2		0.5
SC2-3		1
SC3-1	0.5	0
SC3-2		0.5
SC3-3		1