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Thermal conductivities under unsaturated condition and mechanical properties of cement-based grout for vertical ground-heat exchangers in Korea—A case study

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ABSTRACT

In this study, the thermal conductivities of cement-based grouts for backfilling of vertical ground-heat exchangers were investigated under the saturated, air-dried and unsaturated conditions. The mechanical properties including the p-wave velocity, elastic modulus and Poisson's ratio also were measured. The mix proportions applied were quartzite sand/cement ratios of 1, 1.5, 2, 2.5 and 3, with a fixed water/cement ratio of 0.7. Mixed-grout specimens were prepared in both rectangular parallelepiped shape (11 cm × 6 cm × 4 cm) and cylindrical shape (5 cm dia. × 10 cm height). Their thermal conductivities decreased linearly with decreasing degree of saturation. Also, as the sand/cement ratio was increased, the thermal conductivity at the same degree of saturation was higher, and the thermal conductivity decreased more steeply as the degree of saturation decreased. Based on these results, an empirical equation representing the relationship between the degree of saturation and the thermal conductivity of the cement-based grouts was derived. The results obtained in this study are expected to be utilized as input data for thermal and mechanical behavior analyses of ground-heat exchangers and their installations.

1. Introduction

In general, heating, ventilation, and air conditioning (HVAC) systems are the largest contributors to energy consumption in buildings [1], and various attempts to improve their energy efficiency have been made [2–5]. Among the most energy-efficient and cost-effective HVAC technologies on the current market are the ground-source heat pump (GSHP) system, which accesses and utilizes the heat energy of the earth, energy that is both environmental friendly and inexhaustible [6–10]. GSHP systems are used for heating and cooling residential and commercial buildings [11]. In the winter, they absorb heat from the ground (under which the temperature is higher than above), collect it, and then circulate it within the indoor space of a building; in the summer, they extract surplus heat and dissipate it into the ground (under which the temperature is lower than above) [12]. The ground-heat exchanger, the major component of a GSHP system, is classified as the horizontal or vertical type according to its installation method [13]. This component is integral to the determination of initial GSHP investment and performance. In Korea, the vertical type usually is used [14]. In installing the vertical-type GSHP system, a borehole is drilled into the ground, into which a U-loop HDPE pipe, connected to the heat pump, is inserted, and through which water or antifreeze is circulated. The borehole is then backfilled with grout materials, which provide for efficient heat transfer between the heat exchanger and surrounding soils or rocks, and also act as a hydraulic barrier against pollution from aquifers. Therefore, grout materials need to have both high thermal conductivity and low hydraulic conductivity; moreover, they must have high workability for easy injection within the borehole [12,15,16].

Typical grout materials for the vertical ground-heat exchanger are bentonite and cement [17]. The cement-based grouts are relatively inexpensive and easy to work with [18]. To assess the overall applicability of cement-based grouts, Park et al. [12], in a series of laboratory experiments, evaluated thermal conductivity (under the saturated and air-dried conditions), unconfined compression strength (UCS) and equivalent hydraulic conductivity. Also, Lee [19] derived the optimum mix design for cement-based grout from measurement of UCS and thermal conductivity under the saturated and air-dried conditions, numerical analyses, and in-situ thermal response tests. The UCS of the grout material is not a main parameter of vertical ground-heat exchanger design. Nonetheless, if a ground-heat exchanger is constructed beneath or adjacent to the building structure, it might be considered. Moreover, it provides

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Table 1
Chemical composition of Ordinary Portland cement.

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

Table 2
Chemical composition of quartzite sand.

	SiO_2	Al_2O_3	Fe_2O_3	K_2O	TiO_2	CaO	MgO	Ig-loss
wt%	99.6	0.1	0.03	–	0.02	Trace	Trace	0.1

Table 3
Mixing ratios of grout.

Specimen no.	Water/cement ratio	Sand/cement ratio
SC-1	0.7	1
SC-1.5		1.5
SC-2		2
SC-2.5		2.5
SC-3		3

important information for the energy pile [11]. In any case, the mechanical properties of the grout can be used as input parameters in numerical analysis for the purposes of life-cycle modeling and determining the behavioral characteristics of hardened grout subjected to ground stresses [20].

The thermal properties of soil or rock are known to be affected by moisture content, unit weight, and porosity [21–24]. It is reasonable to assume that fluctuation of the groundwater level will affect the moisture content and, in turn, the thermal conductivity of both grout material and the ground. Characterization of those properties prior to installation is key to GSHP performance, as their direct measurement is practically impossible afterwards. In order to represent the parabolic relationships between thermal conductivity and the volumetric water contents of bentonite-based grouts, Kim et al. [25] proposed several empirical equations.

In the present study, the thermal conductivities with varying moisture contents of cement-based grouts for vertical ground-heat exchangers were investigated. Additionally, the grouts' mechanical properties including UCS, p-wave velocity, porosity, absorption, elastic modulus and Poisson's ratio were evaluated.

2. Experimental platform and procedure

2.1. Materials

Grout materials are required to have thermal conductivities similar to those of geologic formations (1.7–2.1 W/mK) in the ground [26]. However, the thermal conductivity of pure cement grout (0.80–0.87 W/mK) is lower than those of geologic formations [27]. Usually, thermal conductivities can be improved by mixing grouts with additives such as sand, blast-furnace slag and graphite powder [11,14,15].

The cement utilized in this study was Ordinary Portland cement (ASTM Type I), the chemical composition of which is listed in Table 1 [28]. Quartzite sand (crushed sand) having a specific gravity of 2.65 was utilized as the additive. The chemical composition of the quartz sand is shown in Table 2 [29], and its grain-size distribution is plotted in Fig. 1.

2.2. Specimen preparation

The mix proportions applied in this study were quartzite sand/cement ratios of 1, 1.5, 2, 2.5 and 3, with a fixed water/cement ratio of 0.7 (Table 3), based on an optimum mix design proposed in a previous study [19]. For each mix proportion, one

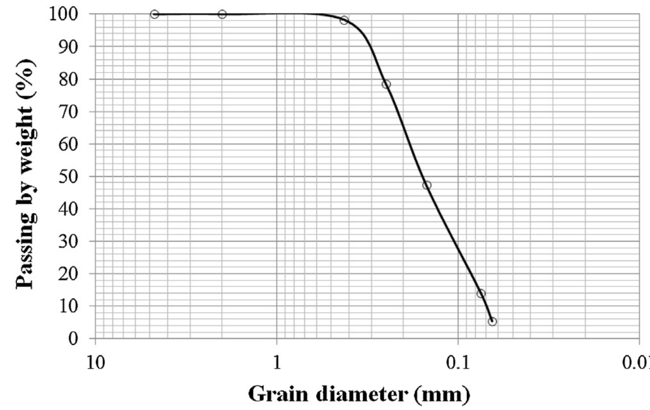

Fig. 1. Grain-size distribution curve.

Fig. 2. Experimental set-up: QTM-500.

rectangular parallelepiped-shape (11 cm × 6 cm × 4 cm) specimen and five cylindrical specimens of NX-size (5 cm dia. × 10 cm height) were prepared. The rectangular parallelepiped-shape specimens were used to measure the thermal conductivity, while the cylindrical specimens were used to measure the p-wave velocity, porosity, absorption, elastic modulus and Poisson's ratio. Specimens were cured in air (23 ± 2 °C, 65 ± 10% R.H.) for 28 days, after which their surfaces were polished with sandpaper for precise measurement of thermal conductivity.

2.3. Measurement of thermal conductivities and mechanical properties

A Quick Thermal Conductivity Meter (QTM-500, Kyoto Electronics Manufacturing Co., Ltd.) was used to measure the thermal conductivity (Fig. 2). The QTM-500, incorporating the model PD-11 probe (size: 95 mm × 40 mm), adopts the transient hot-wire method to measure thermal conductivity in the 0.023–12 W/mK range (repeatability: ±3%; accuracy: ±5%). Changes in the moisture content of the specimens can be represented by the degree of saturation

$$S = \frac{W_{act} - W_{dry}}{W_{sat} - W_{dry}} \times 100 \quad (1)$$

where S is the degree of saturation (%), W_{act} is the specimen weight at the moment of thermal conductivity measurement (g), and Wd_{ry} and W_{sat} are the specimen weights under oven-dried and saturated conditions (g), respectively.

After the specimens were oven-dried at 105 ± 2 °C for 3 days, their dry weights (W_{dry}) were measured. Then, after water