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Viscosity and salinity effect on thermal performance of bentonite-based grouts for ground heat exchanger

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ABSTRACT

Due to its high swelling potential and low hydraulic conductivity, the bentonite-based grout has been popularly used to backfill a borehole constructed for a closed-loop vertical ground heat exchanger in a geothermal heat pump system. In this study, three types of bentonites were compared in terms of viscosity and thermal conductivity. With the consideration of the groundwater inflow, the viscosity and thermal conductivity of the bentonite grouts having bentonite contents of 5%, 10%, 15%, 20% and 25% by weight were also examined. To evaluate the effect of salinity in the coastal area on the swelling potential of the bentonite, volume reduction tests were performed. And in order to reproduce the particle segregation of bentonite–sand mixture when the bentonite-based grout has relatively low viscosity, the segregation was observed using a ring-type separable test apparatus.

1. Introduction

The need to develop alternative energy resource is rapidly growing in preparation for the era of hefty oil prices worldwide. Especially, the United Nations Framework Convention on Climate Change (UNFCCC, i.e., Kyoto Protocol, 1997), which was enhanced and ratified in December 2009 in Copenhagen, and eventually effective since 2013 in order to limit the emission rate of greenhouse gasses. Thus, the role of alternative energy resources is becoming more important.

Among the systems which use renewable energy resources, the geothermal heat pump system or ground source heat pump (GSHP) system is a preferable alternative energy system because it uses the energy from the heat of the earth, which is environmentally friendly and inexhaustible. According to the US Environmental Protection Agency (US EPA), the GSHP system is the most energy efficient, environmentally clean and cost effective space heating and cooling system among others (US Environmental Protection Agency, US EPA, 1993). In South Korea, the GSHP system was first introduced in 2000, and it is anticipated that the market size of GSHP will increase to approximately 1.5 billion USD in 2030 (Korea Energy Management Corporation, KEMCO, 2007).

In a typical GSHP system, to extract or release thermal energy from or into the ground formation, a conventional water-source heat pump unit is coupled with ground heat exchangers (GHEs) where heat exchange occurs between a working fluid circulating through the GHE and the subsurface strata (Lamarche et al., 2010; Lee et al., 2010). Usually, the vertical closed-loop GHE is most popular in Korea that is equipped with a single U-loop or a double U-loop HDPE (High-density polyethylene) pipe in a borehole of 100–300 mm in diameter and 50–200 m in depth (International Ground Source Heat Pump Association, IGSHPA, 1988). The dimension of GHE should be determined by the energy demand of buildings and the ground conditions (IGSPHA, 2000; Pahud and Matthey, 2001; Han et al., 2005; Choi et al., 2008).

After inserting the HDPE pipe, the borehole should be backfilled to make this annulus section isolating from the ground surface. Therefore, increasing the thermal conductivity of the grout material in the ground heat exchanger will improve the efficiency of heat exchange performance of GHEs, and thus reduce the installation cost for GHE along with shorter borehole requirement (Remund and Lund, 1993; Gehlin, 2002; Zheng et al., 2003; Lee et al., 2010; Desmedt et al., 2012).

The bentonite-based grout has been accepted in practice as an excellent sealing material to backfill a borehole for a closed-loop vertical GHE in a GSHP system because of its high swelling potential and low hydraulic conductivity (IGSPHA, 2000). In practice, the neat bentonite grout is usually mixed with fillers, such as silica sand, to enhance the thermal conductivity of bentonite grouts (Remund and Lund, 1993; Remund et al., 1993; Han et al., 2005; Sohn and Shin, 2006). In addition, the acceptable groutability of grout materials should be guaranteed during the installation of GHE in order to fill completely the annulus without any gaps that may cause thermal discontinuity. An optimum viscosity of bentonite slurry should be obtained especially when

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mixed with fillers because if the viscosity is too high, it is extremely difficult to mix thoroughly the two materials, on the other hand, the fillers can segregate from the bentonite slurry at the considerably low viscosity (Remund and Lund, 1993; Heiberger and Remund, 1997). In this paper, a series of volume reduction tests was performed to observe possible repercussion effects of salinity on the swelling potential of bentonite-based grouts around coastal areas.

2. Materials

Three types of bentonite provided in Korea were chosen for this study. Bentonite 1 is a low grade bentonite which is used for the casting process and Bentonites 2 and 3 are produced for the purposes of civil engineering construction such as a mixture for a landfill liner or bentonite slurry. The X-ray diffraction (XRD) test was adopted to analyze the mineral constituents of bentonite. Table 1 presents the mineral components of the three bentonites. Plagioclase and montmorillonite are main components of the bentonite samples.

For enhancing the thermal properties of bentonite-based grout, silica sand has been mixed with backfill materials such as bentonite or cement (Remund and Lund, 1993; Allan, 2000; Han et al., 2005; Sohn and Shin, 2006; Lee et al., 2010). The silica sand which was selected for this study is used for casting steel or construction materials and has over 95% content of SiO_2. The thermal conductivity of the silica sand in fully saturated condition is 2.67 W/m · K on average (Choi et al., 2008).

3. Methods

3.1. Viscosity & thermal conductivity measurement

Heiberger and Remund (1997) recommended that the viscosity of the bentonite-based grout should be controlled because viscosity of bentonite-based grout increases with time. In this study, the viscosity of bentonite-based grouts was measured using a vibration-type viscometer of which the measuring plate vibrates at a frequency of 30 Hz. The measurable viscosity range of the viscometer is from 0.003 to 120 P (g/cm · s). In order to investigate the isothermal change in the viscosity with time after mixing bentonites, an acrylic case coated in a water jacket to circulate the water at a constant temperature of 20 °C (i.e., room temperature) around the grout sample is used as shown in Fig. 1. The device to measure the thermal conductivity of bentonite is the TP02 system (Hukseflux, US), which is equipped with a needle type probe, and adopts the infinite line-source model (Carslaw and Jaeger, 1947). The bentonite content was predetermined as 5, 10, 15, 20 and 25% of the grout slurry weight, which may correspond with the grout mixture design for GHE in practice. The measurement of viscosity and thermal conductivity are recorded every 1 h for 6 h.

3.2. Volume reduction tests

If the bentonite-based grout is imposed by cations, such as the sea water, the volume of the bentonite-based grout can be changed (Yukselen-Aksoy et al., 2008). The diffuse double layer theory (van Olphen, 1963) explained that the thickness of the double layer decreases with the increasing concentration of the pore solution. For example, if the GHE is constructed near a coastal area, the bentonite-based grout can come in contact with saline water (salinity of groundwater in specific southern coastal area of Korea shows 3.3% (KODC, 2013)). The electronic valence in the clay is counteracted by the exchangeable cations in the interlayer. The thickness of double layer decreases with an increase in pore solution concentration (i.e., high salinity). The volume reduction of the bentonite-based grout is the movement of the water hydrating the cations in the diffuse double layer towards the interlayer free water, in order to counteract its high salinity. This reduction in the swelling potential is explained by an osmotic effect through an imaginary semipermeable membrane (Olson and Mesri, 1970; Shackelford and Lee, 2003; Mitchel and Soga, 2005; Yukselen-Aksoy et al., 2008). Consequently, the volume of the bentonite-based grout in the GHE may reduce when bentonite-based grout is exposed with sea water in coastal areas.

In this study, to evaluate the effects of salinity, a series of volume reduction tests was performed with 20% of ball-milled bentonite by weight (bentonite:water = 1:4) at different NaCl concentrations (0.1 M, 0.25 M, and 0.5 M). A 1000 mL cylinder was used to measure the height of the bentonite-based grout during the volume reduction test. The cap of the cylinder was sealed to avoid the evaporation of water during tests. A volume reduction ratio is defined as the reduced volume of bentonite normalized by the initial bentonite volume. The volume reduction test was ceased when the volume reduction ratio approaches an asymptotic value.

3.3. Particle segregation phenomenon

If the bentonite-based grout which has a relatively low viscosity is mixed with the silica sand, the silica sand can segregate from the bentonite dispersion and settle on the bottom of borehole. Thus, there can be a difference in the thermal conductivities of the top and bottom portions of the GHE. The bottom portion of the GHE may have higher thermal conductivity than that of the top portion.

In order to reproduce this phenomenon in the laboratory, a ring-type separable test apparatus was devised as shown in Fig. 2. The bronze ring is 15 cm in diameter and 1.5 cm thick, and equipped with a guide plate for separating each ring when the segregation test is ceased. The sample is divided into four subsections from the top to the bottom of the sample (each subsection includes 5 rings with the total height of 7.5 cm) after the bentonit–sand mixture was poured into the apparatus for 2 days. Then the samples at each subsection were extracted for measuring the thermal conductivity and the remaining rate of silica sand.

The thermal conductivity of each sample layer was measured by the TP02 system in wet condition. The retaining rate is defined as the amount of silica sand retained at the #100 sieve normalized by the total amount of silica sand for convenience. In the current segregation test, two bentonite-based grouts (bentonites 1 and 3) containing 10% and 20% content of bentonite by weight were considered. The amount of silica sand was added by 30% of the total weight of the bentonite–sand mixture.

Table 1
Mineral composition and swelling index of bentonites.

Sample no.	Contents of mineral (%)									Swelling index (ml/2 g)
	Quartz	Plagioclase	K-feldspar	Hornblende	Calcite	[a]Mt	Opal	Pyrite	Sylvite	
Bentonite 1	4.1	58.0	–	–	1.9	30.6	3.8	–	1.7	13.5
Bentonite 2	3.1	52.1	–	–	0.3	38.8	5.5	–	0.2	15
Bentonite 3	6.8	29.2	–	9.0	2.0	42.8	3.3	0.9	6.0	24.5

[a] Mt: montmorillonite.