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Research Paper

Investigation on thermal and moisture migration performance in sand combined with graphite

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HIGHLIGHTS

- The thermal and moisture diffusion behaviors in sand/graphite were addressed.
- The average value for the thermal diffusion degree of sand/graphite increased 25%.
- The thermo-physical properties between raw sand and sand/graphite were compared.
- Graphite additive can improve the thermo-physical properties of sand.
- PAM additive can improve the water-retention of sand-based backfill materials.

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ABSTRACT

The thermal and moisture diffusion behaviors in backfill materials play a key role on the long-term operation performance for the ground source heat pump systems. The thermal and moisture migration characteristics in sand based on a lab-scale setup were determined in terms of the heating temperature (35–45 °C), initial moisture content (10–20%) and the additive (5 wt% graphite). The thermo-physical properties of the sand, and sand/graphite blend were also evaluated. The effect of the anionic polyacrylamide (PAM) on the water retention ability of sand was examined. The values of the thermal diffusivity for the dry sand, and dry sand/graphite blend were 3.745×10^{-7} and $4.396 \times 10^{-7}\ m^2\ s^{-1}$, respectively, which increased linearly with the initial moisture content from 0 to 10%, and then decreased slightly with the initial moisture content from 10% up to 20%. The thermal and moisture diffusion ranges enlarged with the increasing initial moisture content and heating temperature, as well as the addition of the graphite. In comparison with raw sand, the average value for the degree of the thermal diffusion of the sand/graphite blend increased by about 25%. PAM additive in sand/graphite was favorable to ensure long-term operation performance of the GSHP system.

1. Introduction

Shallow geothermal energy is one of the promising renewable energy, which can be efficiently utilized in ground source heat pump (GSHP) systems [1]. The higher comfort level, lower running cost and less impact on the environment also open new opportunities for the application of GSHP [2]. The thermal conductivity of the backfill materials is an essential parameter for designing a GSHP system. The increase in the thermal conductivity of backfill materials leads to a reduction of the thermal resistance between the buried pipes and the surrounding soils, which is expected to be a major approach to improve the heat transfer performance and shorten the required length of the buried pipes [3].

Lee et al. [4] performed a series of in-situ thermal response tests in six vertical closed-loop ground heat exchangers to evaluate the effective thermal conductivities of different grouting materials (cement and bentonite) and additives (silica sand and graphite). They noted that the cement grouting possesses higher effective thermal conductivity than

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Nomenclature

a	thermal diffusivity ($m^2 s^{-1}$)
b	length of the heating plate (m)
c	specific heat capacity ($J kg^{-1} K^{-1}$)
F	surface area (m^2)
I	electric current (A)
L	length of the channel (m)
m	mass (kg)
PAM	polyacrylamide
q	heat flux ($W m^{-2}$)
S	saturation
t	time (s)
T	temperature (°C)
U	heating voltage (V)
x	distance to heating end (m)

Greek letter

γ	ratio of peak value to initial value
ε	porosity
λ	thermal conductivity ($W m^{-1} K^{-1}$)
ρ_a	apparent density ($kg m^{-3}$)
ρ_b	packing density ($kg m^{-3}$)
ρ_s	density of the solid matrix ($kg m^{-3}$)
σ	thickness of the sample (m)
φ	dimensionless temperature
ω	moisture content (d.b.)

Subscripts and superscripts

h	heating end
i	initial state
p	peak
ω	moisture content

that of the bentonite one, and that graphite has better performance over the silica sand as a thermally enhancement additive. A series of in-situ thermal response tests of U-pipe borehole heat exchangers with different backfill materials (bentonite and quartz sand) were conducted by Pahud and Matthey [5]. And they indicated that the thermal resistance of the quartz sand-based backfill material is 30% lower than that of the bentonite one, and the quartz sand is recognized to be a favorable backfill material.

The thermally enhancement additives in backfill materials can be mixed with soil or sand to promote the heat transfer performance of the ground heat exchanger. Delaleux et al. [6] addressed that the thermal conductivity of the bentonite grouts can be enhanced by the addition of graphite, and pointed out that the thermal conductivity of the bentonite/10% graphite grouts is about five times higher than that of the raw bentonite. Jobmann and Buntebarth [7] examined the effects of additives (quartz sand and graphite) on the thermal conductivity of the bentonite-based backfill materials, and highlighted that the thermal conductivity of the bentonite/quartz sand mixture with adding ratio of 50% increased by about 50%, whereas the bentonite/graphite mixture with the same adding ratio increased by 8.5 times in comparison with the raw backfill materials. Therefore, the graphite can be considered as a much efficient additive in the backfill materials for improving the performance of the ground heat exchanger due to its high thermal conductivity and low chemical reactivity [7]. Nevertheless, the high level of the graphite content in the backfill materials could give rise to the increase in the grout viscosity, which would lead to the gap formed between the buried tube and the borehole during the grouting process, which may induce thermal discontinuity and mechanical failure [8]. Therefore, Delaleux et al. [6] also suggested that the blending ratio of graphite should be less than 10%.

During a long period of run for the GSHP system, the moisture content in the backfill materials around the buried tubes would decrease, which can make the grout tend to shrink, and create cracks and voids in the area surrounding the tubes, which would lead to increasing substantially the thermal resistance [9]. In addition, the COP value of the GSHP system decrease with the reduction in moisture content of the backfill materials, which leads to more electricity consumption [10]. Therefore, in order to ensure the GSHP system to be in a good working condition for years, the water retention capacity of the backfill materials should be improved to reduce the moisture migration and enhance the heat transfer performance of the ground heat exchanger.

Moreover, the water-soluble anionic polyacrylamide is identified as a highly effective soil erosion-preventing polymer because of its water retention capacity and extremely low aquatic toxicity [11–13]. Lentz and Sojka [14] highlighted the effects of the anionic polyacrylamide on the crop yields over a 7-yr period of continual treatment, and they found that yearly soil loss of soil/PAM reduced by 66–99% in comparison with the raw soil. Wei et al. [15] evaluated the water-saving of PAM in a crop filed, and noted that the application of PAM into soil has a certain promoting effect on the water retention, and that the soil water content increases by 6–11% compared with the raw soil. Li et al. [16] also noted that thermal diffusivities and water retaining of the soil are enhanced with increasing the polyacrylamide additive from 1.5% to 3.0%. Wan et al. [17] addressed that the PAM additive (0.27% blending ratio) in backfill materials has a positive effect on the heat transfer of the ground heat exchanger.

As stated above, the most of works highlighted the effect of the graphite on the thermal conductivity of the bentonite-based backfill material. However, the thermo-physical properties, and the thermal and moisture diffusion characteristics of the sand-based backfill material in terms of graphite and PAM additives are still not enough to date.

The current work presents the thermal and moisture diffusion, and the thermo-physical properties in the sand-based backfill material. The effects of the heating temperature, initial moisture content and graphite additive on the thermal and moisture diffusion behaviors of the sand are evaluated. The thermo-physical properties of the raw sand are compared with the sand/graphite blend at different moisture contents. The water retention ability of the PAM additive mixed with the backfill materials is also examined through a long-term experiment. This study can attribute to a reference for the design of GSHP system.

2. Materials and methods

2.1. Experimental materials

The raw sand was obtained from Beijing, China. The graphite powders were purchased from HuiHua Chemical Products Co., Ltd (Zhengzhou, China). The PAM powders were supplied by JiaLin Water Treatment Technology Co., Ltd (Beijing, China). The size distributions, mean diameters, specific surface areas of the sand, graphite and PAM particles were measured by a laser particle size analyzer (Malvern MS2000, UK). The size distributions of the sand, graphite and PAM particles ranged from 40 to 595 μm, from 1 to 1000 μm and from 40 to 1200 μm, respectively. The surface weighted mean diameters of the sand, graphite and PAM particles were 106, 17 and 405 μm, respectively. The volume weighted mean diameters of the sand, graphite and PAM particles were 217, 126 and 551 μm, respectively. The specific surface areas of the sand, graphite and PAM particles were 0.057, 0.345 and 0.0141 $m^2 g^{-1}$, respectively. The raw sand was uniformly spread on a plastic film and processed by air-drying for a month. The sand