Construction and Building Materials 162 (2018) 732–739

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Durability of geothermal grouting materials considering extreme loads

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HIGHLIGHTS

- Four different grouting materials with high water/solid ratios have been characterized.
- Their suitability as grouts for ground source heat pumps has been evaluated.
- The durability of the grouts against wet-dry and freeze-thaw cycles has been assessed.

ARTICLE INFO

Article history:
Received 12 June 2017
Received in revised form 9 November 2017
Accepted 9 December 2017

Keywords:
Ground source heat pump
Grouting material
Thermal conductivity
Mechanical performance
Permeability
Durability

ABSTRACT

The concern about the massive use of the non-renewable and very limited fossil fuels together with the well-known effects of the global warming makes it more necessary the efficient use of the current forms of renewable energy generation. Because of the crucial role played by the grouting materials in the Ground Source Heat Pumps (GSHP), a proper selection of these elements should be made based on a deep knowledge of their performance. In this paper, thermal conductivity, mechanical strength and grout-pipe permeability of four different highly workable grouts have been tested before and after they were subjected to wet-dry and freeze-thaw durability treatments. Results obtained demonstrated the harmful effects of using a large amount of mixing water in grouts subjected to those extreme loads. However, the use of these type of grouts with very good workability is still possible in GSHP installations with balanced thermal designs provided that regular operational and environment conditions are considered.

1. Introduction

Around 40% of the worldwide energy is consumed to provide buildings with lighting, heating or cooling [1]. Today, many of the systems used to supply all these services are not as efficient as would be desired and cause the emission of greenhouse gases (GHGs) into the atmosphere. However, the environmental consciousness and awareness of the actual impact is growing in the last few years.

The shallow geothermal energy systems or ground source heat pumps (GSHP) are becoming more and more popular as one of the most efficient forms of renewable energy. Through these systems, the heat is exchanged with the ground by means of a pumped water/glycol fluid that flows through a buried pipe. Between the pipe and the ground, a grouting material is needed that provides the borehole with essential properties. In summer time, the sensible heat from the water/glycol fluid is transferred by convection and conduction through the pipe wall (radiation can be neglected) and then by conduction through the grout until the grout/ground interface, from which the heat is transferred to the ground mostly by conduction. When pipe-grout and grout-ground contacts are not good enough, the convection process in these interfaces becomes more important. In winter time, the heat moves in the opposite direction by means of the same heat exchange mechanisms. From the environmental point of view the proper sealing provided by the grout would act as a hydraulic barrier along the borehole to avoid cross-contamination of different aquifers and transport of surface contaminants to aquifers. Furthermore, a high pipe-ground heat exchange rate would result in a decrease of the borehole length and hence, in the reduction of the installation costs and the return of investment period. Finally, an appropriate mechanical performance of the grouting material would provide the required stability of the borehole against ground loads, temperature fluctuations or harmful debonding problems [2]. Still, when it comes to the construction stage of the GSHP installation, highly flowable grouts are preferred to the detriment of materials fulfilling all those properties. This is because of the higher workability,

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https://doi.org/10.1016/j.conbuildmat.2017.12.072
0950-0618/

which makes the pumping operation easier. Something similar happens with other applications, where grouts are required to have very good flow properties [3] along with other characteristics.

Bentonite is a well-known material widely used by drilling and geothermal energy related companies. Workability and low permeability are main advantages of this material, whereas low thermal conductivity and volumetric instability are probably the main drawbacks. Most of the authors deal with the thermal conductivity of bentonite-based grouts and mortars and the way this property can be enhanced by adding silica sand [4] or different forms of graphite [5–7]. The addition of these fillers resulted in higher conductivities of the tested grouts. As for cementitious grouts, the influence on their effective thermal conductivity was studied when silica sands [2,8–11], steel sands, steel grits or steel fibres [8] and steel slags [12] were used in different gradations. In all these cases, higher conductivities were obtained as compared to neat cement grouts, whereas potential borehole length reductions of 22–37% were estimated for a grout with a thermal conductivity three times higher instead of the neat cement [9,13].

Different cement-based grouts were also subjected to tests that determined their hydraulic and mechanical behaviour. More specifically, infiltration tests and mechanical push out tests were developed in order to evaluate the sealing performance of the grouts and the bond quality at the grout-pipe interface [2,14,15,16]. Results from the tests showed the very low permeability of both the neat cement and cement-sand grouts themselves. However, the permeability increased when the same test was applied to grout-pipe specimens, probably due to the presence of pathways at the interface. On the other hand, a superior sealing quality was obtained for the cement-sand grout as compared to the neat cement grouts, what agrees with the higher mechanical bond strength measured for cement sand-grouts.

Durability is an indispensable requisite for grouting materials that might suffer from freeze-thaw and wet-dry loads during their lifetime. Freeze-thaw cycles are likely to occur when GSHP systems are not properly balanced and the winter heating loads are much larger than the summer cooling loads. As for the wet-dry cycles, they play a key role when the GSHP installations are located in areas with variable water tables. A severe damage due to any of these events could eventually result in an increase of the borehole thermal resistance and therefore, a decrease of the GSHP thermal performance. Likewise, this damage could also impact the environment.

According to [14,15], the hydraulic conductivity of cement-sand grout/pipe specimens slightly increased as a result of applying wet-dry loads, whereas neat cement specimens critically cracked after the treatment. In this sense, the addition of steel fibres to cement-based grouts was shown to improve the cracking resistance of the material and mitigate the increase of permeability that wet-dry cycles involve [17]. As for the effect of freeze-thaw cycles, Erol and François [18] evaluated the influence of the permeability of silica-sand and calcite based grouts on their cracking resistance due to the thermal stress induced by freezing loads. Also, the effect of freeze-thaw cycles on the mechanical and thermal performance of cement-sand grout/pipe specimens was negligible as reported in [19]. Finally, the compressive strength of cementitious grout/pipe specimens exhibited certain decrease when −5 °C/50 °C cycles were applied [20].

In order to narrow the gap and consolidate the knowledge on this issue, the durability of four different grouting materials with high water/solid ratios for workability (pumping) purposes has been evaluated in this paper as a continuation of the research published in a previous one [21]. Thus, the suitability of these grouts has been discussed based on their thermal, mechanical and hydraulic behaviour both before and after extreme conditions in the form of wet-dry and freeze-thaw loads were applied.

2. Materials and methods

Along the research that made possible this paper, four different grouts consisting of Type I Portland cement, bentonite clay, silica sand and graphite flakes were considered as typical in the construction of GSHP installations. Proportions (by weight) of the solid fraction of the grouts are presented in Fig. 1 whereas the composition including the mixing water as well as the corresponding water/solid (w/s) and water/cement (w/c) ratios are shown in Table 1. As can be seen in Fig. 1, the grouts here analyzed have decreasing and increasing contents of cement and bentonite, respectively. As for the sand and graphite, grouts G1, G2 and G3 keep a similar global amount of these components (25%), although G1 consists of sand only whereas in G2 and G3 both components exist that are distributed in the opposite way. While in G3 the use of bentonite is aimed to improve the plastic properties of the grout, the high content of the clay in G4 comes from the need of keeping the sand in suspension to avoid sedimentation.

According to this composition, the behaviour of G1 was expected to be influenced by the higher amount of cement and the moderate (in this context) w/c and w/s ratios. Based on the cement content and the still moderate (when compared to G2) w/s ratio of G3, a comparable behaviour before the durability treatment should be expected from this grout despite the higher use of bentonite. As for G2, results should be cleary influenced by the much higher amount of mixing water used, which is linked to the extensive use of graphite as enhancing additive. Finally, the particular composition of G4, with a very high s/c ratio and a extensive use of bentonite, should make a difference as compared to the other grouts.

For the characterization of the grouts at laboratory level, typical tests were performed according to EN and ASTM standards: fresh and hardened density, water-accessible porosity, bleeding and Marsh Funnel (MF) viscosity. Results were as expected [21] and therefore, all the grouts were considered suitable for the durability assessment.

For the preparation of the different grout specimens, a 750 W mortar mixer with variable speed was used. The power of this mixer was assumed high enough based on the fluid consistency of the grouts. Fresh grouts were cured for 48 h under laboratory conditions. Following, molds were removed and the specimens were immersed in water at 20 °C for 28 curing days. Finally, mechanical, thermal and hydraulic-infiltration tests were carried out on the grout specimens before and after they were subjected to repeated freeze-thaw and wet-dry cycles. One tailor-made and two standard types of specimens were used to comply with the requirements of the different laboratory tests [21]: thin solid cylinders for the thermal conductivity tests; hollowed cylinders with one embedded HDPE pipe for the hydraulic tests; and a rectangular prism for the mechanical strength tests. Specific easy to cut and handle PVC molds were arranged for the first two types of specimens while standard metal molds were used for the third one.

Grout were exposed to 28 freeze-thaw cycles and up to 14 wet-dry cycles, lasting 24 h and 9 days per cycle, respectively. For the first 8 h of each freeze-thaw cycle, specimens were placed in a freezer at a temperature of −10 °C, while for the last 16 h they were placed in a water tank at ambient temperature (+20 °C). As for the wet-dry cycles, specimens were placed in a water tank at ambient temperature (+20 °C) for 7 days and then introduced in a drying oven at 40 °C for the following 2 days.

Four different tests were carried out on the grouting materials before and after the extreme loads were applied. Thermal conductivity values in accordance with the ASTM 5334-08 standard were obtained after 0, 7, 14, 21 and 28 freeze-thaw cycles and after 0, 7 and 14 wet-dry cycles. Three measurements were taken with the TP02 probe of the Hukseflux TPSYS02 system from each of the three specimens used per type of material and load applied. This Non-Steady-State Probe (NSSP) method, also known as transient line source, with conductivity and temperature ranges of 0.1–6 W/mK and −55 to 180 °C, respectively, complies with the standard followed.

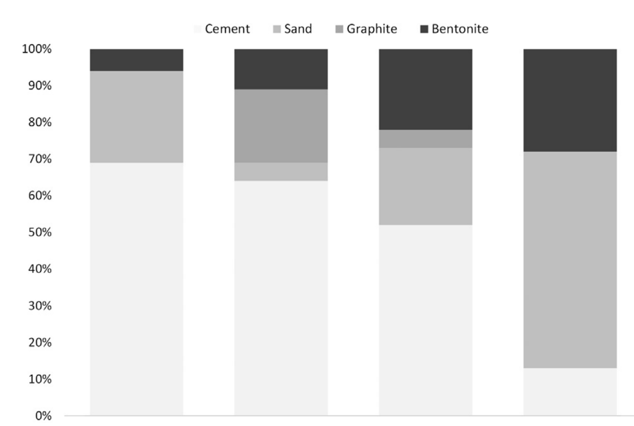

Fig. 1. Proportions (by weight) of the solid fraction of the grouts considered for study.