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Experimental analysis of enhanced cement-sand-based geothermal grouting materials

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HIGHLIGHTS

- Nine cement-sand-based admixtures with improved properties were characterized.
- Different sands and advanced additives were used for the fluid mortars design.
- Thermal and mechanical properties were assessed, including pipe-mortar bond strength.
- Good ratios of thermal to mechanical performance were obtained.
- Mortars were subjected to wet-dry cycles for durability assessment.

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ABSTRACT

Nowadays, Ground Source Heat Pumps (GSHP) are achieving significant efficiencies, mostly because of the development of their electromechanical components. However, concepts such as the technical performance of the grouting materials deserve more profound analysis, as becoming essential in areas where good potential thermal performance of the GSHP and serious risks of groundwater contamination exist. In this paper, several fluid mortars with enhanced characteristics have been evaluated. Results show improved mechanical and thermal properties compared to conventional grouting materials. Likewise, mortars exhibited good performance after being subjected to durability treatment. For now, the cost of some mortars may constitute a barrier.

1. Introduction

The use of fluid mortars for grouting is widespread in construction. In fact, besides all the very well-known applications in the fields of the civil and building engineering, another application can be highlighted in the last few years that requires the development of specific admixtures: ground source heat pumps (GSHP). Due to its very favourable features, including lower energy consumption and GHG emissions, renewable and clean energy or independence of supply, this technology, widely implemented in countries such as Sweden or Germany for more than 30 years, has also become very popular in countries such as Spain, where other renewable technologies such as solar or wind energies are much more developed [1]. Moreover, the significant thermal efficiencies achieved are removing typical barriers to the evolution of this technology, such as the high initial investment required. Closed-loop GSHPs with vertical boreholes acting as ground heat exchangers are the most common geothermal installation worldwide, with depths ranging from 90 to 200 m. Between the heat carrying fluid flowing through the pipe and the ground a backfill material normally known as grouting material is placed, which provides thermal coupling, borehole wall stability and environmental ground protection [2]. This is indeed a very important element of the GSHPs, not only due to its influence on the system's thermal efficiency, but also because of the potential problems of contamination of aquifers that a poor-quality grouting material might cause [3,4,5].

Although the research done in the last few years is not extensive, some investigations can be highlighted, such as those where the thermal conductivity of different bentonite-based grouts with different types and quantities of sands and graphites is evaluated [6,7]. A more thorough characterization was carried

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out in [8–13], where mechanical strength, thermal performance and permeability of bentonite-based grouts were analysed before and after they were subjected to freezing damage and heating-cooling cycles. The favourable influence of the graphite on the thermal performance of the grouting materials, its adverse effect on the mechanical behaviour and the negative impact of the high w/s (water/solid) ratios of the very workable admixtures, are some of the important conclusions of these investigations. As for cement-based materials, thorough research was done in the early 2000 s [2,14–17] throughout which a superplasticized cement-based grout was designed that resulted in better thermal and mechanical performance than neat cements or bentonite-based grouts. In [18,19], the authors incorporated other materials such as electric arc and blast furnace slags, construction and demolition waste or steel fibres with the aim of achieving higher thermal conductivities and improved mechanical behaviour as well as permeability, respectively. The durability of cement-based grouts was evaluated in [20,21] by means of testing mechanical and thermal performance of several admixtures mainly made up of cement and natural and recycled sands, respectively. Lately, other investigations have been published that deal with problems arising during mixing, placement or with residence time, such as the decreasing values of conductivity when there is poor control of water content [22] or when the level of saturation changes [23].

Thus, little research has been done so far on the suitability of this type of materials. However, new applications related to GSHP systems are showing up, such as deep borehole heat exchangers [24], geothermal District Heating [25,26] or Smart Grids using geothermal energy [27]. At the same time, the research on the use of advanced (nano-) materials in conventional construction materials like mortars or concretes [28,29] is rapidly increasing. All in all, it seems that further research about grouting materials is required, especially for GSHP installations where the risk of contamination of groundwater is higher and so the use of enhanced materials is a must. To that end, an analysis of the characterization of several types of cement-sand-based fluid mortars with different sands and additives has been carried out in this paper. In addition, their performance has been evaluated when they are subjected to wet-dry cycles, something very common in situations when water table and heat play a role.

2. Materials and methods

2.1. Materials and properties

Four types of mortars with different mix proportions have been designed that are made of cement, water, superplasticizer, two types of aggregates (limestone and silica) and two different carbon-based additives: flake graphite and expanded graphite. The cement type CEM II-B (V)/32.5R (EN 197- [30]) was selected simply for availability reasons. The main criteria for the selection of the aggregates were local availability of the limestone and the considerably better thermal properties of silica sand [14]. As for the additives, the former is a naturally occurring form of graphite with purity over 94%, which is typically found as flat, plate-like crystals with angular edges. The nanosized expanded graphite is produced from natural graphite by chemical oxidation and expansion at high temperature, reaching expansion ratios of 200–300 and purities over 99%. As well as the well-known properties of flake graphite (e.g. thermal and electrical conductivity or chemical stability) worm shaped expanded graphite was assumed to contribute with its higher surface area and sealing properties, among others. Neither of the additives are water soluble so, in contrast to what occurs with heavy metals, toxic substances are not expected to be generated in the groundwater. In addition, they are not bioavailable and have very low chemical reactivity. The different morphology of the two additives can be identified in Fig. 1.

Finally, a powdered superplasticizer and cohesion promoter (MasterCast 205 MA) with bleeding prevention effect was used, which is especially recommended for the design of good quality self-levelling mortars with improved flowability. Table 1 shows the specific gravity and water absorption of the aggregates and graphites used, as well as their particle size distribution. Sands with a maximum aggregate size less than 2 mm were used for workability purposes.

In Table 2 the nine different mix proportions (M1 to M9) are shown. The amount of water used for the design of the mortars was determined based on the flow table consistency test (EN 1015-3 [31]). Given the application studied here, diameters over 300 mm were desired resulting in mortars having good fluid properties yet retaining suitable mechanical and thermal properties. The amount of superplasticizer used was kindly suggested by the provider.

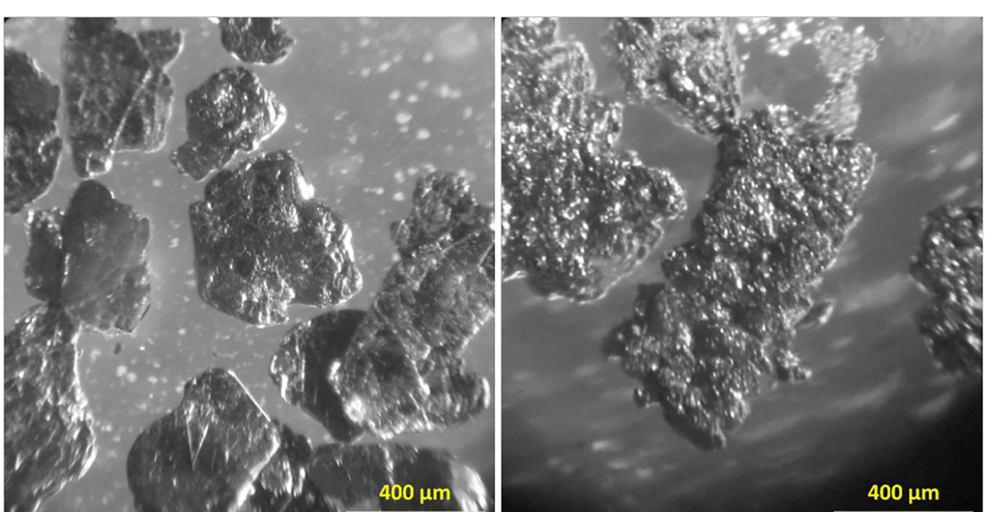

Fig. 1. Optical micrographs of the flake graphite (left) and expanded graphite (right) used in the research.