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Study of different grouting materials used in vertical geothermal closed-loop heat exchangers

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HIGHLIGHTS

- ► All the mix proportions satisfied consistency and strength requirements imposed.
- ► All aggregates used improve the neat cement Effective Thermal Conductivity (ETC).
- ► Mix aggregate proportion increase improved the ETC for all but the CDW sand.

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ABSTRACT

As a renewable source, low-enthalpy geothermal energy is becoming more relevant in heating and cooling buildings, by using an adapted heat pump to exchange thermal energy with the ground. Vertical closed-loop geothermal systems exchange heat with the ground through a closed buried pipe system, sealed with a grouting material that ensures the stability and thermal transmission of the borehole. Different grouting materials have been tested recently, which use cement or bentonite as a base material. However, the use of recycled materials, which might contribute to the sustainability of the project, has not yet been studied. This paper analyzes the use of different natural and recycled aggregates as main constituents in cement-based mortars. Results show that all mixes fulfill the minimum consistency and strength requirements. The use of any of the aggregates proposed improves the thermal conductivity compared to the cement mortar on its own, independently of the proportion used. Limestone sand, silica sand and electric arc furnace slag enhance the thermal conductivity of the grout as its proportion of use increases. However, no satisfactory results have been obtained for Construction and Demolition Waste-based mixes because of their high water requirement.

1. Introduction

Due to the increasing fossil fuel prices and global warming effect, some leading countries have started to search for new renewable energy sources. According to Omer [1], 40% of the worldwide energy is consumed in lighting, heating and cooling buildings. Most heating and cooling systems use fossil fuels or air-based heat pumps, which have low efficiencies and emit CO_2 and NO_x, thus contributing to the global warming process. Geothermal energy has proven to be a clean, efficient source, which has, moreover been declared renewable by the European Union 2009/28/CE directive [2]. A geothermal heat pump system takes advantage of the year-round constant ground temperature to obtain higher efficiencies than conventional air to air or air to water heat pumps. Instead of using ambient air as a heat source or sink, geothermal pumps use the ground as a heat exchanger.

According to Florides [3], ground heat exchangers are divided into two main groups, open and closed geothermal systems. Open geothermal systems use the existing groundwater directly to exchange heat with the ground, extracting it from a shaft or injecting it to the ground. Closed geothermal systems use a heat carrying fluid which flows through a buried pipe circuit and exchanges heat indirectly with the ground. There are two main advantages that made closed geothermal systems more interesting than open ones. On the one hand, they do not need to have an aquifer to be operational, widening their field of application. On the

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other hand, even when an aquifer is available their influence on the groundwater table is smaller than that of open systems, except for large geothermal borefields, where thermal affection must be further evaluated.

At the same time, closed systems are classified in two main groups, depending on the geometry of the resulting heat exchanger. Horizontal closed-loop systems, which are buried at depths up to 5 m, are affected by exterior climate conditions. Because of the low depth needed, horizontal systems are easy to install and hence, economical when a land plot is available. However, this is not applicable in many places where land is scarce. Vertical closed-loop systems, also called Vertical Ground Loop Heat Exchangers (VGLHE) are a possible option when there is little available land. A closed pipe circuit is introduced into a vertical borehole reaching depths of up to 200 m. The stability of the borehole walls is ensured by injecting a grouting material, but at the same time, this material must present good thermal properties to transmit heat from the pipes to the ground or vice versa.

Philippacopoulos, Allan et al. [4,5] simulated the temperature of the grouting in a simple U shape VGLHE, evaluating the influence of the grouting, pipe placement and bonding strength on the grouting temperature distribution. They concluded that bonding quality between pipe and grout is more significant than that between grout and the existing ground. They also added that gaps diminish the heat flux in the pipe surroundings, decreasing the efficiency of the system, thus grouting with high shrinkage when drying should be avoided. Influence of the grout to formation thermal conductivity ratio in heat transfer is also analyzed by Smith and Perry [6], concluding that thermal conductivity of the grout should be equal to or greater than the formation's not to decrease the system efficiency. Finally, Chulho Lee et al. [7] proposed a thermal conductivity range of 1.7–2.1 W/(m K) for grouts combined with most existing ground types.

According to Allan and Philippacopoulos [5], cement alone and bentonite mixes, with a thermal conductivity of 0.80–0.87 W/(m K) and 0.75–0.80 W/(m K), respectively, were predominantly used in the United States until 2000. However, these values were significantly reduced by the loss of water, due to the high porosity of the grouts. Bentonite-based grouts have been improved significantly in the last decade. Smith and Perry [6] tested the performance of bentonite-based grouts in a real installation, comparing standard bentonite grouts to the enhanced bentonite–cement sand mix. Carlson [8] compared the performance of the enhanced bentonite grout proposed by Smith with standard bentonite grouts concluding that the total borehole length required could be reduced by 10% in the former case. Chulho Lee et al. [7] improved the thermal conductivity of the grout either by using silica sand or graphite. They demonstrated greater improvement when graphite was used, obtaining up to 3.5 W/(m K) of thermal conductivity for the resulting grouting materials. Recently, Delaleux et al. [9] used Compressed Expanded Natural Graphite to enhance bentonite grouts, obtaining a thermal conductivity of 5 W/(m K), hence this grout could be used in most existing ground types. However, Delaleux et al. [9] also warned that for each 10% reduction in water content by weight there is a reduction in the thermal conductivity of the grout by 1 W/(m K). In dry state, graphite enhanced bentonite grouts have values ranging from 1.5 to 2 W/(m K), due to the volume shrinkage of the mix.

The grouting materials studied in this paper are also intended to provide a preliminary analysis of the grouting materials used for thermally active foundations, which require a compressive strength similar to that of the usual structural concrete. As bentonite-based grouts do not fulfill this minimum strength requirement, cement-based grouting materials are proposed instead. Geothermal mortars have not been fully investigated in the last decade. Allan and Philippacopoulos [10] presented a complete characterization of different cement-sand based mortars, studying, the influence of superplasticizer and the aggregate type on the rheologic, mechanic, hydraulic and thermal properties. As a consequence, Allan and Philippacopoulos [5,10,11] presented a superplasticized cement-sand mortar to be used as grouting material, obtaining a thermal conductivity of 2.42 W/(m K) which only reduced to 2.16 W/(m K) when oven dried. However, all the proposed aggregates were silica-sands or quartzite sands. Therefore, the final objective of this paper is to analyze the possibility and/or convenience of using different aggregates as the main material in geothermal grouting materials.

2. Experimental methodology

2.1. Materials

All the mortars designed are made of water (w), cement (c), superplasticizer (sp) and different types of aggregates (s). CEM II-B (V)/32.5R type cement has been chosen in agreement with EN 197-1 [12]. This cement is a mix of Portland cement and up to 35% of siliceous fly ash by weight, valid for the use in foundations. Its compressive strength is greater than 10 and 32.5 MPa at an age of 2 and 28 days, respectively.

Silica (S), Limestone (L), Electric Arc Furnace slag (EAF) and Construction and Demolition Waste (CDW) sands have been chosen as basic aggregates. Silica and limestone sands are common natural aggregates in Spain. EAF slag is a by-product of the steel-making process of Global Steel Wire in Santander. Its use as coarse and fine aggregate of concrete has been successfully demonstrated by many authors [13–15]. However, the CDW aggregate used in this research does not have any application in Spain at this time. The original CDW comes from a crushed-concrete recycled aggregate plant. The final commercial product is a 0–60 mm recycled coarse aggregate, obtained after a crushing and selection process. The first step of this process consists of cleaning the raw material, thus eliminating all the surface imperfections before crushing it. As a result, a 0–6 mm sized recycled-sand aggregate is obtained, which has until now been discarded because the current Spanish structural concrete standard (EHE08) [16] does not allow the use of CDW recycled aggregates with a size of less than 4 mm. In this research, maximum grain size is limited to 2 mm in all the aggregates to ensure the pumpability of the mix, according to Allan [11].

Grain-size distribution of the aggregates by weight was determined according to EN 933-1 (Table 1) [18]. Both EAF slag and CDW lack fines, hence limestone filler (F) was proposed to correct their size distribution. Apparent particle density (ρ_s) and water absorption was also obtained according to EN 1097-6 [17], showing significant density differences between aggregates. As a consequence, volume-weighted grain-size distribution was evaluated to determine the replacement factor of EAF and CDW with limestone filler, resulting in 25% and 10% replacement factor by weight,

Table 1
Specific gravity and water absorption (EN 1097-6) and grain-size distribution of the aggregates (EN 933-1).

Aggregate	Specific gravity	Water absorption	Sieve size (mm)						
			4	2	1	0.5	0.25	0.125	0.063
			Passing percentage						
L	2.71	0.52	100	99	61	40	28	21	16
S	2.65	0.16	100	100	80	67	47	26	17
EAF	3.82	1.83	100	100	39	11	5	3	2
CDW	2.57	5.07	100	100	73	48	29	19	12
F	2.753	N/A	100	100	100	100	97	89	75