PAPER 6

Analysis and study of different grouting materials in vertical geothermal closed-loop systems

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ABSTRACT

In vertical closed-loop geothermal systems, the material used to fill the boreholes is an essential element since it facilitates the exchange of heat between holes and pipes which contain the heat transfer fluid. Therefore, the thermal conductivity of this grouting material plays a vital role in conducting heat to the installation; not only does it increase its efficiency with higher thermal conductivity values, but it also makes the reduction of the total drilling length required to cover some particular energetic needs, possible. In view of the importance of this grouting material, a series of mixtures were produced and both thermal and mechanical properties were analysed in the laboratory. The use of aluminium shavings and sulpho-aluminate cement improved the thermal conductivity of these mixtures and offered excellent mechanical properties. However, non-satisfactory results were obtained for the bentonite due to the contractile effects caused in samples of this nature.

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1. Introduction and background

As a renewable, efficient and environmentally-friendly source, geothermal energy is, at the moment, in an expansion process, which places it at a very important position in the energy sector. With respect to very low temperature geothermal energy, commonly used to produce SHW (Sanitary Hot Water) or to heat/cool a certain place [6], heat exchangers can be divided into two main groups: open and closed geothermal systems. Open systems use groundwater coming from an adjacent aquifer to exchange heat with the ground, while closed systems use a fluid flowing inside a pipe to carry out the thermal exchange. The latter system is not conditioned to the existence of a nearby aquifer to provide the water exchange. Closed systems can be classified as: horizontal closed-loop systems, in which pipes are buried up to 5 m, and vertical closed-loop systems, constituted by deeper vertical drillings [16]. The grouting material injected inside these holes must fulfil a series of functions. It must guarantee the stability of holes and pipes. It must constitute a hydraulic barrier, avoiding the pollution of close aquifers due to a possible leak. Finally, grouts must allow the heat exchange between ground and pipes fluid. This last function will determine the right working and efficiency of the installation; hence one of the most important properties of grouting materials is the thermal conductivity or the capacity to conduct heat. Fig. 1 shows the schematic of a geothermal borehole [19].

Numerous authors have analysed the thermal conductivity of a wide variety of grouting materials to discard those materials whose thermal properties make them unsuitable for use as grout in these installations. As a rule, it is considered important that the grouting material has a thermal conductivity value equal to or higher than that of the surrounding ground, so as to avoid reducing the efficiency of the system. It should also be noted that the possible gaps (pores of different geometry filled with air or water) in the grout negatively affect the installation reducing the heat flux to the pipes [2,21,24,26,37]. Grouting materials are typically grouped into grouts whose primary components are either bentonite or cement. Bentonite is flexible, with low permeability and easy placement, although it has a relatively low thermal conductivity: a range of between 0.65 W/(m K) and 0.90 W/(m K) in saturated conditions [11]. It is, however, commonly used in geothermal boreholes in spite of its limited capacity to conduce heat. In order to improve this thermal property, the addition of other materials to bentonite has been analysed. Remund and Lund [20], demonstrated that the thermal conductivity of bentonite is substantially improved by the addition of sand and can vary by modifying the water content of the mixture. Allan and Philippacopoulos [27], elaborated a mixture

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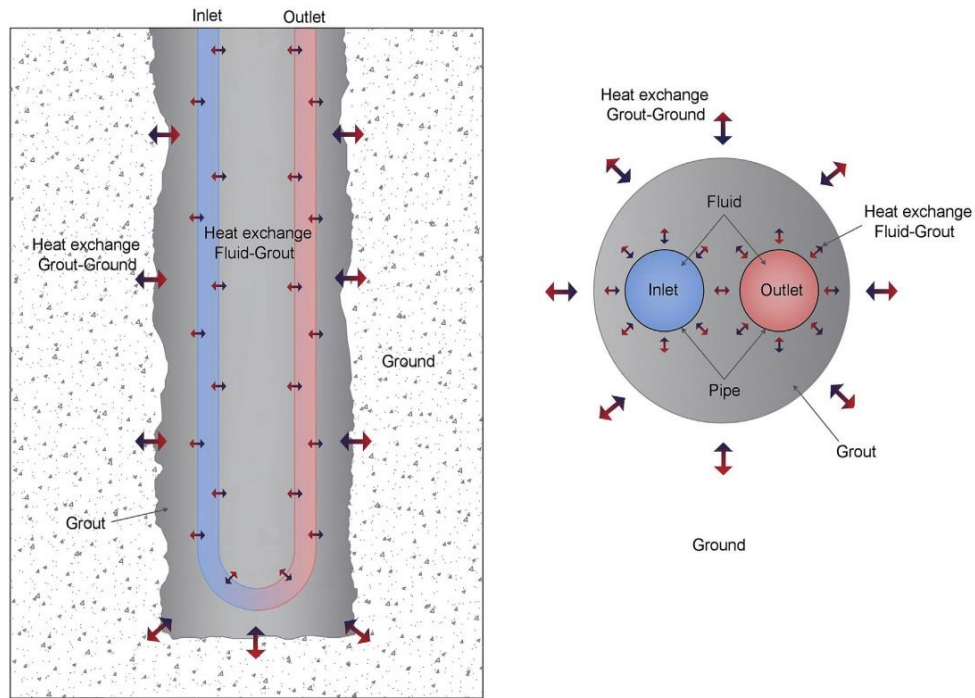 *E-mail address:* u107596@usal.es (C.S. Blázquez).

Fig. 1. Two different views of a geothermal borehole.

enhanced with silica sand which tripled the thermal conductivity of a bentonite mixture. Jobmann et al. [25], studied the influence of adding graphite to the grouting material and recorded a thermal conductivity of 3 W/(m K) for a mixture with a basis of bentonite constituting 14% water and 15% graphite. Lee et al. [8,9], noted that by increasing the quantity of silica sand and graphite, the thermal conductivity of the sample increased; although so did its viscosity. In this way, by adding 30% graphite; they attained a thermal conductivity of 3.5 W/(m K). They also obtained 2.6 W/(m K) of thermal conductivity for a mixture of cement, silica sand and graphite. Delaleux et al. [14], have recently pointed out that by adding less than 15% of graphite powder, thermal conductivities of around 5 W/(m K) can be achieved. Engelhardt [18], added ballast to bentonite, acquiring thermal conductivities up to 2.6 W/(m K). The shrinkage potential of bentonite is another important factor to be considered. In this field, Olson and Mesri [35] focused on the impact of pore fluid on the volume change of bentonites under various stress states.

With respect to cement based mixtures, the addition of silica sand was studied in depth by Allan et al., [28–32]. They demonstrated that the total drilling length could be reduced by around 22–37% with the use of this grout, depending on the type of ground and the diameter of the drilling in question. Xu and Chung [44] proved that by adding silica sand to cement, the thermal conductivity of the mixture increased by 22%. Alrtimiri et al. [1], made mixtures with different amounts of sand, cement, fluorite, glass and PFA (Pulverized Fuel Ash) obtaining thermal conductivities of up to 2.88 W/(m K) for a PFA of 20%. Recent studies based on energy piles deal with the use of cement as concrete in deep foundations [7,23,34].

The main objective of the present research is to suggest new alternatives, suitable to be used as grouting materials in a geothermal installation. On the basis of the information mentioned before, experiments with grouts that incorporate aluminium as a new element were carried out. Thus, a series of test tubes of different materials (including aluminium) were produced and analysed to check its suitability as geothermal grouting materials. Aluminium was added to the grouts in two ways: from a batch of cement or added to the mixture separately. Parameters like thermal and hydraulic conductivity, workability, compression strength and the possible contractions or reductions of volume over time have been considered in this work.

The innovative element in these mixtures is aluminium, which, due to its extraordinary capacity to conduce heat, was incorporated in the shape of cement and shavings or small filings. Thus, its cohesion with the rest of components of the mixture was significantly easier.

2. Experimental methodology

2.1. Materials

Specimens produced in laboratory are composed by: water (w), sodium bentonite (b), silica fine-grain sand (s), detritus from a hole

of granitic origin (d), cement portland CEM II-B (c_c), super-plasticizer (sp), sulpho-aluminate cement ALI CEM (c_a) and aluminium shavings (a). Bentonite, silica sand and CEM II-B are commonly used for this purpose. Superplasticizer was tested in some mixtures to analyse its influence. It allows the improvement of the pump-ability of the mixture avoiding at the same time its segregation. Detritus (d) were taken from a drilling placed in the province of Ávila (Spain) in a granitic ground. Its grain distribution can be seen in Fig. 2.

Sulpho-aluminate cement supplied by FYM (*Heidelberg Cement Group*) is a conglomerate constituted by a sulpho-aluminate clinker of calcium and high quality anhydrite [15]. It provides a rapid development of the initial resistances for the medium and long term, exceeding the values given by high output portland cement.

"Aluminosis" is the term given to a series of chemical and physical transformations that reduce the hardness, strength and compactness of the concrete constituted by aluminium cement. This cement provoked structural problems, especially during the third quarter of the twenty century [3]. However, its use is thoroughly regulated by normative *UNE-EN-80310:96* [43]. This fact does not result in an inconvenience in the possible utilization of this material as grout in geothermal drillings because its function differs from that required for the support of large structures. Its use, therefore, would be totally feasible in these renewable installations. Both aluminium cement and cement portland used in this research fulfil the specifications considered in the normative *EN 197-1* and *EN 197-4* [39,40].

Aluminium, used as metal in the form of shavings, was previously crushed in order to reduce its size and consequently guaranteeing the correct uniformity of the mixture. It is important to highlight there is not any risk of chemical reactions with other components from the ground given the chemical behaviour of this element and the poor proportion in the mixtures. Table 1 shows the main characteristics of the two kinds of cements that are part of this study.

2.2. Mixtures

Cylinder specimens of 5 cm in diameter and 11 cm in height were used to test the different mixtures studied as grouting materials. The amounts of each of the components of the mixtures were set according to the results observed by other authors cited in Section 1. This way, the advisable ratios in dry conditions among the different aggregates (g) and cement (g/c_c and g/c_a) are around 1,
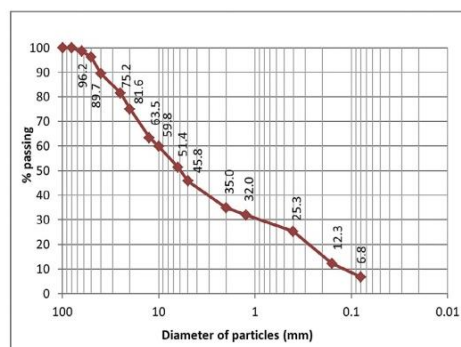
Table 1
Main characteristics of sulpho-aluminate cement (ALI CEM) and cement portland (CEM II-B).

	ALI CEM	CEM II-B
Principal chemical components	CO: 37–41% Si_2O: $\leq$ 9% Al_2O_3: 27–33% Fe_2O_3: $\leq$1.5% SO_3: 10–14% MgO: $\leq$ 5%	Clinker: > 65% ashes + limestones: < 30% SO_3: <2.4% Chlorides: < 0.003% Chromium VI soluble in water: <0.0002%
Setting time	Initial- 25 min Final- 50 min	Initial- 200 min Final- 300 min
Compression resistance	7 days- 42.5 MPa 28 days- 47.5 MPa	7 days- 28.0 MPa 28 days- 40.0 MPa

Main applications	■ Refractory concrete
	  - Base and temporal bench
	  - Constructions and prefabricated elements of bulk concrete or non-structural concrete
	  - Certain cases of foundations of bulk concrete
	  - Sprayed concrete
		- Concrete slab for roads
		- Bulk and reinforced concrete
		- Mortars and bricklaying's
		- Concrete with reactive arid
		- Concreting in hot weather
		- Compacted concrete dam
		- Soils stabilization
		- Non-structural prefabricated

2 and 3. In the present research the relation was set in g/c_c and $g/c_a = 2$. For those samples that incorporate superplasticizer (sp), the defined ratio was sp/c_c and $sp/c_a = 0.02$ [36]. With regard to sand and bentonite mixtures, a percentage of bentonite equal to 10–12% was selected because it provides a notable value of thermal conductivity [17]. With respect to aluminium shavings, several sand-shavings mixtures saturated to 80% with water were tested, modifying the percentages by weight of aluminium in relation to the total dry weight of the sample. The aim was to establish the most appropriate amount of aluminium in relation to the thermal conductivity results. Table 2 shows the thermal conductivity results of each mixture of sand-shavings tested.

As can be seen in Table 2, it gets to the point where increasing the amount of aluminium shavings actually reduces the thermal conductivity. An excessive amount of shavings causes the appearance of an increasing number of holes that alters the thermal conductivity of the sample. In the manufacture of the rest of the grouts, the quantity of aluminium was set at 1.0% of total weight of the dry sample, given that it has a thermal conductivity value very close to higher percentages of shavings but using a lower amount of aluminium.

The quantity of water added to each mixture depends in each case on the absorption capacity of the integrated materials. In any case, the aim was that every resultant specimen has the suitable consistency to be easily injected into a hole, making their use as

Fig. 2. Grain distribution of the detritus used in mixtures 10, 11 and 12.

Table 2
Thermal conductivities for the different percentages of shavings in sand-shavings mixtures.

Percentage by weight of aluminum shavings (%)	Thermal conductivity (W/mK)
0.5	3.270
1.0	3.651
1.5	3.692
2.0	3.752
2.5	3.860
3.0	3.798
3.5	3.620

grouting material, possible. Abrams cone method defined by the Spanish Law *UNE 83313:1990* (annulled *by UNE-EN 12350-2:2006*) [42] was used to define the consistency of the samples. According to this method, the consistency of all samples was fluid (category S4 in Abrams cone method), with variable ratios (w/c_c and w/c_a) in function of the different aggregates that constitute the mixtures. As an alternative to this method, the Marsh funnel [5], which is commonly used as an indicator of bentonite-based grouts viscosity, could also be used in this research. Table 3 contains the mixtures made in laboratory and the components of each of them.

2.3. Laboratory samples characterization

With the purpose of suggesting the most suitable grout in geothermal installations, a series of laboratory tests were carried out for each of the samples presented in Table 3. These tests made it possible to determine the aptitude of these materials as geothermal grouts.

2.3.1. Density and workability

Every specimen analysed in this study containing cement (c_c or c_a) among other components as well as the remaining mixtures, behave like fluids and have the appropriate consistency to inject them into a borehole (to a particular depth and without any extra mechanical means). In order to carry out a complete characterization of cement mortars, densities of fresh mortar and after 28 days of hardening were calculated. For the rest of samples (without cement), only the initial density was calculated. In any case, the amount of water added to the samples was set according to Abrams cone method, so none of them generate difficulties during the injection into the hole.

2.3.2. Thermal conductivity

Thermal conductivity is an essential property to be considered in a grout. However, the effect of increasing the conductivity of the grout on the overall efficiency of the borehole heat exchanger (BHE) is highly limited by the ground conductivity.

Thermal conductivity of laboratory specimens was determined using KD2-PRO analyser with sensor RK-1(Fig. 4) developed by Decagon Devices [12]. Its operation is based on the infinite line heat source theory and computes the thermal conductivity by monitoring the dissipation of heat from the needle probe. Heat is applied to the needle for a set heating time *th*, and temperature is measured in the monitoring needle during heating and for an additional time equal to *th* after heating. The temperature in the needle during heating is deduced from Equation (1) [10].

$$T = m_0 + m_2t + m_3lnt \tag{1}$$

Where:

m_0 is the ambient temperature during heating
m_2 is the rate of background temperature drift
m_3 is the slope of a line relating temperature rise to logarithm of temperature

Equation (2) represents the model during cooling [7].

$$T = m_1 + m_2t + m_3ln\frac{t}{t - t_h} \tag{2}$$

Both equations (1) and (2) are used by the equipment to provide the temperatures during the period of heating and after it when heating stops and needle starts cooling. Fig. 3 shows the evolution of temperatures during a process of measuring of KD2-PRO.

Thermal conductivity can be calculated from Equation (3) that also considers the heat flux (q).

$$k = \frac{q}{4m_3} \tag{3}$$

Only 2/3 of the data collected are used during heating and cooling (it ignores early-time data) since these equations are long-time approximations to the exponential integral equations. This approach prevents errors derived from the placement of the needle. Equations (1) and (2) can be solved by linear least squares, giving a solid and more adjusted result [22,38].

In the current research, sensor RK-1 (3.9 mm in diameter and 6 cm in length) was used to determine the thermal conductivity of each sample (Fig. 4). This sensor is capable of measuring the thermal conductivity in a range between 0.1 and 6 W/(m K) with ±10% of accuracy. The relatively long read times of sensor RK-1 (around 10 min) contribute to prevent errors derived from the large diameter needle and the contact resistance between the sensor and the granular sample and solid materials. The contact between needle and tested material is guaranteed by placing thermal grease (a ceramic polysynthetic thermal compound) in the hole where the needle is situated. Drilling could increase the uncertainty on results. Three samples of each mixture were made and three measurements were carried out for each of these samples to evaluate the uncertainties. It is advisable to mention that the RK-1 sensor was previously calibrated with samples supplied by the manufacturer. Measurements with KD2 Pro can be strongly affected by wrong practices. To obtain the most accurate data possible, ambient
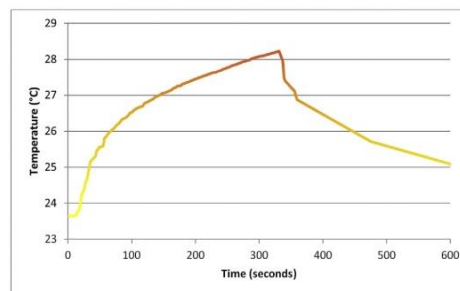
Table 3
Compositions of each of the tested mixtures, where: s-sand, b-bentonite, d-detritus, c_c- cement portland, c_a- aluminium cement, a-aluminium shavings, sp-superplasticizer, w-water.

Mixture	Percentage in relation to total weight (%)							
	s	b	d	c_c	c_a	a	sp	w
1	77.65					0.78		21.57
2	53.18		19.46			0.80		19.16
3	46.14	6.29				0.59		46.98
4	50.00			25.00				25.00
5	40.24	5.49			22.93			31.34
6		19.12			9.56			71.32
7	51.39			25.70		0.76		22.14
8	57.41		30.26			0.87	0.60	10.86
9	57.91			30.52			0.61	10.96
10		74.52						25.48
11		50.00		25.00				25.00
12		50.00	25.00					25.00

Fig. 3. Evolution of temperatures during a process of measuring with KD2-PRO.

Fig. 4. (a) Drilling of a hole to insert sensor RK-1. (b) Measuring of thermal conductivity with equipment KD2 Pro.

temperature was kept as constant as possible during the measurement. If sample temperature changes during the measurement period, it degrades the data and makes it difficult for the inverse calculation to find the correct values for the thermal properties. To minimize these sources of error, about 15 min for samples and needle to equilibrate with the ambient temperature before taking measurements and around 15 min between readings for temperatures to equilibrate.

Once the specimens were manufactured, they were left to dry and harden (in case of mixtures with cement, a period of 28 days, time required so that this material reaches its maximum resistance). After this time, a hole of 6 cm in length and 3.9 mm in diameter (needle size) was drilled to place the sensor RK-1 and carry out the thermal conductivity measurements (three for each sample) always using the thermal paste. Sand mixtures without cement or bentonite were previously compacted in a standard Proctor mould [41] to prepare the test tubes. Pushing of the needle into the prepared soil specimen was carefully made to avoid possible effects of soil densification.

2.3.3. Compression strength

Despite the fact that there is not any specific requirement about the minimum unconfined compressive strength of mortars used as grout in vertical closed-loop systems, it is recommended that these grouts, considered as non-structural concrete, have a compression strength of at least 15 MPa according to the Spanish regulation *EHE08* [33]. Mechanical strength of the grout is important to

guarantee the stability of the borehole and to protect the heat exchangers. Continuing with the characterization of these grouts, compression strength of cementitious mixtures (2, 4, 5, 6, 7, 8, 9, 11 and 12) was determined after 28 days of hardening. After this time, compression tests provided the highest values of resistance that the sample can support before breaking. Simple compression tests were used in this work given that grouting materials mainly supports compression efforts. Freezing impacts in grouts are not considered in this work; otherwise traction strength test should be carried out [13]. In Fig. 5 it is possible to observe the state of one of the test tubes studied before and after the simple compression test.

2.3.4. Volumetric reduction

Another factor studied in the grouts is the reduction of volume and the presence of holes over time. These aspects result in negative effects for the thermal transfer function of a grouting material. The possible gaps created in the grouting material can be refilled with water (in the case of boreholes with the presence of groundwater) or air, deficient thermal conductor that could constitute a barrier in the thermal exchange between ground and pipes. Accordingly, a visual inspection and physical characterization of each test tube was carried out and initial and final dimensions (after 28 days) were measured. Volume reductions were controlled to discard those mixtures unsuitable for use as geothermal grout.

Boundary conditions were previously defined to analyse the contractions. Room temperature was set in 18 °C for all cases. Most tests were performed in unsaturated conditions exposed to air with
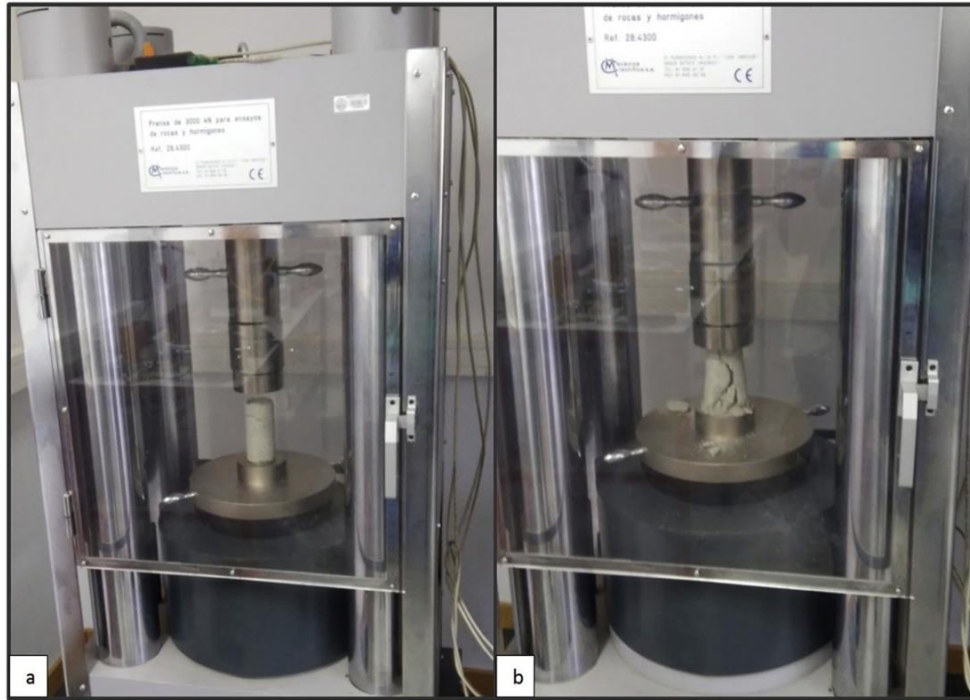
Fig. 5. Simple compression test. (a) Test tube ready to start the test. (b) Test tube after breaking.

the exception of saturated sand grout. Grouts were not subjected to any vertical effective stresses during the period of visual inspection. This research focuses on free shrinkage experiments that may not be representative of the constraints in a borehole. Tests represent the conditions expected near the ground surface that probably change deeper in a borehole.

2.3.5. Hydraulic conductivity

Hydraulic conductivity constitutes another essential parameter in a grout. However, it was verified that saturated sand, mixtures of bentonite or the rest of cementitious samples do not allow any flux of water through them. For this reason, and given that all mixtures used in this work have insignificant (even zero) hydraulic conductivity values, measurements of this parameter are not presented in this research.

3. Results and discussion

3.1. Laboratory test results

Results of the laboratory tests are presented in Table 4. Compression strength results (not presented in Table 4) were all greater than 15 MPa for all cementitious mixtures.

A series of important considerations regarding the grouts analysed in this research can be deduced from Table 4:

Table 4
Laboratory test results. *Values measured in fresh samples, **Values measured after a period of hardening of 28 days.

Mixture	Density [kg/m³] x 10³	Thermal conductivity [W/mK]	Contractions [%]
1	2.44*/2.44**	3.651**	0**
2	1.92*/1.77**	2.199**	0**
3	1.58*/2.04**	1.566**	44.02**
4	2.10*/2.07**	2.453**	0**
5	1.86*/1.68**	1.270**	3.97**
6	1.24*/1.29**	1.096**	27.91**
7	2.15*/2.05**	2.789**	0**
8	1.94*/1.78**	1.016**	0**
9	2.39*/2.24**	1.317**	0**
10	2.39*/2.39**	1.949**	0**
11	2.01*/1.92**	2.036**	0**
12	1.96*/1.87**	1.829**	0**

- Density values measured after the period of hardening of 28 days are in every case equal to or lower than the values corresponding to initial densities, except for those mixtures that experienced a high reduction of volume (mixtures 3 and 6) due to the evaporation of a fraction of water they initially had. The highest densities correspond to sand and detritus mixtures with a degree of saturation of 80% of water (mixtures 1 and 10). The initial and final densities of these samples are identical given that the grout would always be under saturated conditions and therefore its density would not vary. In general, mixtures with

Table 5
Set of thermal conductivity measurements, average and maximum deviation.

Mixture	Thermal Conductivity [W/mK]									Average	Maximum Deviation
	Sample 1			Sample 2			Sample 3				
1	3.652	3.649	3.651	3.650	3.651	3.649	3.652	3.651	3.650	3.651	0.002
2	2.197	2.199	2.198	2.197	2.202	2.198	2.200	2.197	2.199	2.199	0.003
3	1.563	1.564	1.564	1.567	1.569	1.568	1.567	1.565	1.566	1.566	0.003
4	2.457	2.456	2.455	2.452	2.450	2.452	2.454	2.453	2.452	2.453	0.004
5	1.269	1.268	1.269	1.272	1.273	1.270	1.271	1.272	1.270	1.270	0.003
6	1.093	1.092	1.094	1.096	1.095	1.096	1.098	1.099	1.098	1.096	0.003
7	2.789	2.788	2.788	2.786	2.784	2.784	2.794	2.791	2.794	2.789	0.005
8	1.012	1.013	1.014	1.016	1.015	1.016	1.019	1.017	1.018	1.016	0.003
9	1.318	1.318	1.319	1.322	1.321	1.311	1.322	1.321	1.320	1.317	0.006
10	1.948	1.949	1.949	1.952	1.953	1.954	1.945	1.947	1.947	1.949	0.005
11	2.032	2.035	2.034	2.035	2.033	2.033	2.039	2.039	2.04	2.036	0.004
12	1.834	1.832	1.829	1.825	1.827	1.828	1.829	1.826	1.827	1.829	0.005

aluminium shavings (mixtures 1, 2, 3, 7 and 8) do not have the highest values of density. The low density of this element allows the formation of combinations with interesting properties but without increasing the density of these mixtures. Finally, there are no significant differences of density among samples with cement portland (c_c) and those ones constituted by aluminium cement (c_a). In conclusion, the use of aluminium does not generate higher density mixtures than the commonly used for these purposes.

- Thermal conductivity values presented in Table 4 represent the average of the measurements carried out for each mixture (three samples for each mixture and three measurements for sample). Table 5 shows the set of measurements, the average for each mixture and the maximum deviation in these values.

As a rule, all specimens provide quite notable thermal conductivity values. Mixture 1 of saturated sand (s) and aluminium shavings (a) stands out, constituting, from a thermal point of view, an excellent option for those boreholes with groundwater. Mixtures with aluminium cement (c_a) present higher thermal conductivity values than those samples with cement portland (c_c), reaching values of 2.453 W/(m K) as in the case of mixture 4 only constituted by sand and aluminium cement. Aluminium shavings improve, in all cases examined, the thermal conductivity of the sample in question with an amount of only 1% in relation to the total weight of the dry sample. Thus, mixture 7, containing aluminium cement (c_a), sand (s) and aluminium shavings (a), achieves a thermal conductivity value of 2.789 W/(m K) as well as mixture 2 with a thermal conductivity of 2.199 (W/(m K)). Mixtures (10-11-12) formed by detritus (d) from a borehole offer quite acceptable thermal conductivity values, including both saturated detritus (mixture 10) and detritus with cement portland (c_c) (mixture 12) or with aluminium cement (c_a) (mixture 11) which reaches the most remarkable value. Mixtures with bentonite (b) also stand out but in a negative way providing comparatively low values as a result, among other factors, of the low thermal conductivity of this material.

Finally, specimens including superplasticizer (sp) (mixtures 8 and 9), offer lower thermal conductivity values than those ones with similar composition (mixtures 2 and 4) but without this substance. This may be due to the large number of holes observed in these mixtures caused by the use of superplasticizer. Both mixtures were reproduced with identical composition (without superplasticizer) and examined to verify that this element was the source of the increase of holes in these samples. Fig. 6 graphically presents the distribution of thermal conductivities of the group of mixtures.
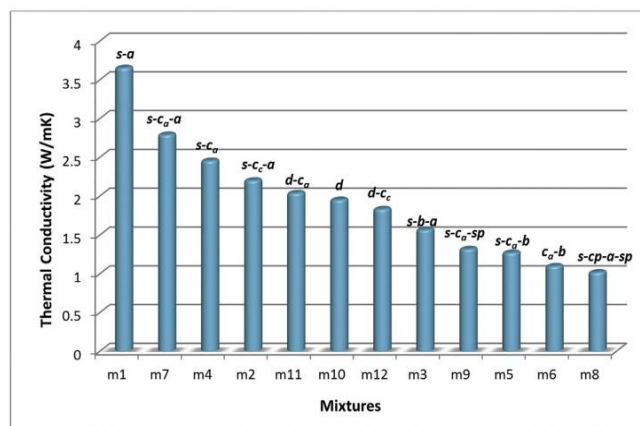

Fig. 6. Graphic of the distribution of thermal conductivities of the mixtures.

- Simple compression tests carried out on mixtures with cement (c_c or c_a) provided favourable results, superior to the recommended 15 MPa, except in mixtures with bentonite (b) which do not get such compression resistance since this material does not allow the complete solidification of the sample. However, the compressive strength is probably not the best indicator of performance in this application; more importance should be given to the shrinkage behaviour and the thermal conductivity of grouts.
- With regard to volume reductions or contractions after a period of 28 days, this phenomenon was observed in all mixtures with bentonite (b). The contractile nature of this material caused strong contractions in the samples, coming to generate volume reductions up to 44.02% in mixture 3 or 3.97% and 27.91% in mixtures 5 and 6 that counteracted this property of bentonite because of the cement they also contained. It is important to highlight these results are representative of a worst-case scenario (near the ground surface, without vertical effective stress and above the water table). The daily evolution of the volume

reductions experimented by mixtures 3, 5 and 6 can be observed in Fig. 7.

Because of the negative impact this grout may cause in vertical closed-loop systems, a more exhaustive study of this phenomenon was carried out. A series of additional specimens made of bentonite-water or bentonite-cement (b-c_c or b-c_a) were manufactured, this time with lower percentages of cement (3%, 6%, 9% and 15% of cement in relation to the total weight of the dry sample). The volume reductions experimented in each case were analysed. In all assumptions studied, high volume decreases were registered, always exceeding the percentages previously expounded in Table 4. Fig. 8 shows the final appearance of the bentonite test tubes after 28 days in comparison with the initial size represented in the central test tube that did not experienced contractions due to the absence of bentonite.

Although all specimens experienced a high degree of contractions, the most extreme case was found in one of the bentonite-aluminium cement samples with an amount of cement of 6% in
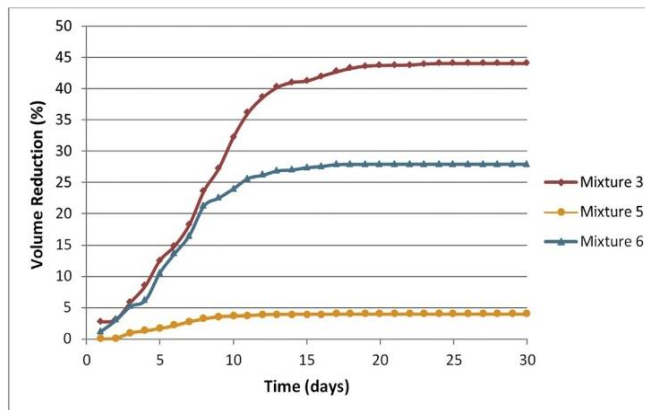

Fig. 7. Daily evolution of the volume reductions experimented by mixtures 3, 5 and 6. *Test were made with an ambient temperature of 18 °C, in unsaturated conditions and not subjected to any vertical effective stresses.
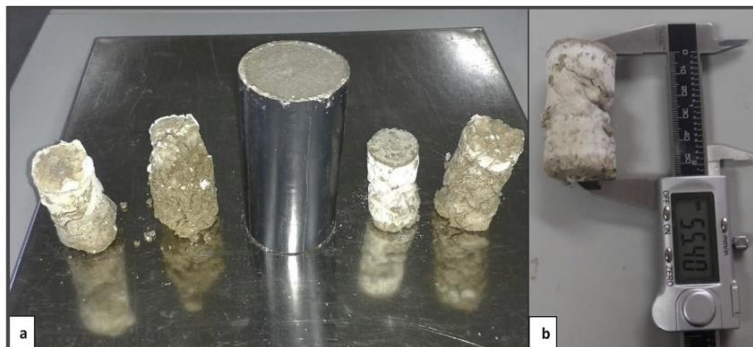

Fig. 8. (a) Comparison of the final appearance of bentonite samples in relation to the central sample exempt of bentonite, (b) Measuring of bentonite sample with a digital calibre.

respect to the total weight of the dry sample. The volume reduction for this sample was of 89.79%. Fig. 9 schematizes the reductions of size this sample experienced.

All experiments were made at constant temperature and humidity. Results denote this grout is not suitable in boreholes without groundwater where almost the totality of water is evaporated. An exhaustive analysis of the borehole conditions should be carried out before choosing bentonite as grout.

3.2. Proposed solutions

Considering the tests made in laboratory, Table 6 indicates those suitable mixtures to be used as geothermal grout in boreholes with groundwater and without it. This Table 6 also establishes the non-recommendable mixtures to this end, because of the size reductions, porosity and hence deficient capacity to conduce the heat these samples have.

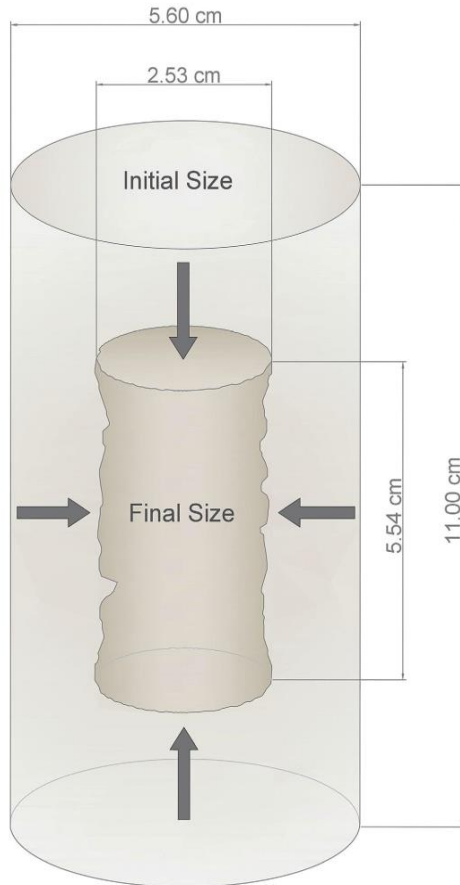The selected solutions for each of the assumptions are

Table 6
Suitability of the proposed mixtures for the two considered assumptions. *Suitable but non-recommendable mixture.

Mixture	Boreholes without groundwater	Boreholes with groundwater
s	✗	✓
2	✓	✓
3	✓*	✓*
4	✓	✓
5	✓*	✓*
6	✓*	✓*
7	✓	✓
8	✓*	✓*
9	✓*	✓*
10	✗	✓
11	✓	✓
12	✓	✓

expounded below.

➢ *Boreholes without groundwater*

In this kind of boreholes, mixtures that require a continuous saturation (mixtures 1 and 10) are totally discarded. The following solutions are highly recommended:

- Mixture 7 (aluminium cement-sand-shavings): apparently, it is the best solution for these types of holes considering that it is the mortar with the most notable thermal conductivity value. It also presents excellent resistance capacities and being simultaneously exempt of contractions.
- Mixture 4 (aluminium cement-sand): this grout, which has an excellent thermal conductivity, means an ideal solution in holes without groundwater because of the same reasons described in the above mixture.
- Mixture 2 (cement portland-sand-shavings): equally recommendable in holes without groundwater due to its proper thermal conductivity and resistance properties with a minimum amount of aluminium.
- Mixture 11 (aluminium cement-detritus): this mortar, that contains the detritus from a borehole, has a moderate thermal conductivity (around 2 W/(m K)), sufficient compression strength and does not present size decreases. However, its aptitude depends on the characteristics of the detritus in question that change thoroughly from a hole to another.
- Mixture 12 (cement portland-detritus): as in the previous case, its ability to be used as grout depends on the particular detritus. In this instance, the mixture means a proper alternative with lower thermal conductivity than the previous solutions but it is equally acceptable because of its resistance capacities and constant volume.

➢ *Boreholes with groundwater*

It can be assumed that grouts are water-saturated in the case that the phreatic level is near the ground surface. The grouts suggested in these conditions are:

- Mixture 1 (saturated sand-shavings): this grout constitutes an appropriate solution, it reaches an excellent thermal conductivity value (>3 W/(m K)), without size reductions and it does not mean an inconvenient from an economical point of view. It would only be applicable to these boreholes since if it was not saturated, its capacity to conduce the heat would sharply descend.
- Mixture 10 (saturated detritus): as in the last mixture, this grout means a proper solution for these cases although it has a lower

Fig. 9. Schema of the size reduction of the sample $b\text{-}c_a$ to 6%.

Dimensions shown in figure: 5.60 cm, 2.53 cm, Initial Size, Final Size, 5.54 cm, 11.00 cm

thermal conductivity. It does not experience volume reductions and does not imply an additional expense since it derives from a borehole.

In addition to these two solutions, for those holes where the presence of water is not completely guaranteed, the circulation is sporadic or the intention is to seal the hole, samples suggested in the previous section (mixtures 4, 2, 7, 11 and 12) are equally suitable and recommendable in these conditions.

Table 7 presents a multi-criteria analysis for mixtures 7 (Option A), 4 (Option B), 2 (Option C) and 1 (Option D). Mixtures 10, 11 and 12 were not considered given that the particular conditions of these samples will depend on the detritus in question. Three criteria were used; criterion 1 (density, workability), criterion 2 (thermal conductivity) and criterion 3 (cost per test tube). The optimal ranking is *DABC* and *DACB*; Option D followed by Option A, followed by Option B, followed by Option C or Option D followed by Option A followed by Option C followed by Option B. In any case, the most optimal option is D, mixture 1. When mixture 1 cannot be used, the optimal ranking is ABC and ACB, mixture 7 will be the most recommendable.

3.3. Environmental and economic impact

It is important to consider the environmental and economic impacts of the different mixtures considered in this research:

- In relation to the environmental issue, most of the mixtures of this research provide a total sealing of the hole, preventing leakages of circulating fluid. Mixtures with bentonite in boreholes without groundwater experience volume reductions, however, this fact should not affect the borehole sealing. Special attention should be paid to mixtures 1 and 10 (sand or detritus saturated and shavings) which could not seal the hole if they are not completely saturated. Another environmental issue is the chemical interaction between compounds of the grouting and the ground. Nature of the components used in the mixtures does not suppose chemical reactions with the surrounding materials of the ground.
- Regarding the economic aspect, the use of aluminium (as shavings or cement) does not mean a significant increase with respect to the rest of grouts commonly used. Also, these grouts contribute to increase the efficiency of the installation generating economic savings in the process of energetic extraction. Table 8 shows an estimation of the cost per test tube of 270.93 cm^3 produced in laboratory.

Although the difference by test tube is quite low, if the hole is considerably deep, the cost of the grout could define its choice. Thus, whenever possible, saturated sand could provide proper results with a relatively low cost.

Table 7
Multi-criteria analysis for mixture 7 (Option A), mixture 4 (Option B), mixture 2 (Option C) and mixture 1 (Option D).

Criteria	Weight	Direction	Option A		Option B		Option C		Option D	
			Performance	Weighted performance	Performance	Weighted performance	Performance	Weighted performance	Performance	Weighted performance
1	0.15	−1	2.15	−0.32	2.10	−0.31	1.92	−0.29	2.44	−0.37
2	0.6	1	2.79	1.67	2.45	1.47	2.2	1.32	3.65	2.19
3	0.25	−1	0.13	−0.032	0.11	−0.027	0.024	−0.006	0.014	−0.003

Outranking Matrix	A	B	C	D
A	0	0.6	0.6	0.15
B	0.4	0	0.4	0.15
C	0.4	0.4	0	0.15
D	0.85	0.85	0.85	0

Policy Ranking Permutation	Policy Parings	Final Score
ABCD	AB + AC + AD + BC + BD + CD	2.05
ABDC	AB + AD + AC + BD + BC + DC	2.75
ACBD	AC + AB + AD + CB + CD + BD	2.05
ACDB	AC + AD + AB + CD + CB + DB	2.75
ADBC	AD + AB + AC + DB + DC + BC	3.45
ADCB	AD + AC + AB + DC + DB + CB	3.45
BACD	BA + BC + BD + AC + AD + CD	1.85
BADC	BA + BD + BC + AD + AC + DC	2.55
BCAD	BC + BA + BD + CA + CD + AD	1.65
BCDA	BC + BD + BA + CD + CA + DA	2.35
BDAC	BD + BA + BC + DA + DC + AC	2.85
BDCA	BD + BC + BA + DC + DA + CA	3.05
CABD	CA + CB + CD + AB + AD + BD	1.85
CADB	CA + CD + CB + AD + AB + DB	2.55
CBAD	CB + CA + CD + BA + BD + AD	1.65
CBDA	CB + CD + CA + BD + BA + DA	2.35
CDAB	CD + CA + CB + DA + DB + AB	3.25
CDBA	CD + CB + CA + DB + DA + BA	3.05
DABC	DA + DB + DC + AB + AC + BC	**4.15**
DACB	DA + DC + DB + AC + AB + CB	**4.15**
DBAC	DB + DA + DC + BA + BC + AC	3.95
DBCA	DB + DC + DA + BC + BA + CA	3.75
DCAB	DC + DA + DB + CA + CB + AB	3.95
DCBA	DC + DB + DA + CB + CA + BA	3.75

Bold letters shows the best options

Table 8
Cost per test tube made in laboratory.

Mixture	Cost per test tube (€)
1	0.023
2	0.027
3	0.035
4	0.090
5	0.098
6	0.079
7	0.101
8	0.038
9	0.127
10	0
11	0.077
12	0.014

4. Conclusions

Grouting material used in vertical closed-loop systems must guarantee a series of thermal, physical and mechanical requirements. In the present research, a set of mixtures were made and analysed by laboratory tests, examining different properties. Specimens were manufactured with a certain consistence (according to flow cone method) to allow their injection in a borehole. Tests allowed deducing the following conclusions:

- Thermal conductivity values of the tested samples are in general considerably notable. The combination of saturated sand-shavings, the mixtures of aluminium cement-sand-shavings and aluminium cement-sand stand out with a thermal conductivity value of around 3 W/(m K). Aluminium shavings contribute to increase the thermal conductivity of a sample with only 1% of the total dry weight. Aluminium cement also improves the thermal conductivity in comparison with cement portland. Mixtures with bentonite or superplasticizer present the lowest values of this thermal property.
- Compression strength tests show that all mortars considered have a resistance superior to 15 MPa (value recommended for non-structural materials) with the exception of those cements that incorporate bentonite to the composition.
- Contractions studies reveal the negative effect that bentonite causes on samples that incorporate it. Thus, the higher amount of bentonite in the mixture, the higher size reductions will experience the test tube over time. These effects reject bentonite as grouting material in this type of installations.
- Finally, a multi-criteria analysis was used to select the most suitable grouts. The first option would be mixture 1 (saturated sand-aluminium shavings) followed by mixture 7 (aluminium cement-sand). In function of the borehole conditions, these mixtures are the most appropriate solutions to be used as grouting materials.

Acknowledgments

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