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THERMAL AND MECHANICAL PERFORMANCE OF GROUTING MATERIALS IN GEOTHERMAL BOREHOLES: IMPLICATIONS FOR HEAT TRANSFER EFFICIENCY AND ENVIRONMENTAL PERSPECTIVE

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Abstract

Grouting materials used in geothermal boreholes represent a key component in the efficient operation of ground source heat pump (GSHP) systems, as they simultaneously control heat transfer between the borehole heat exchanger and the surrounding geological formation while ensuring hydraulic sealing of the annular space between the pipes and the borehole wall. The thermo-hydraulic and mechanical performance of these materials directly influences the long-term energy efficiency of geothermal systems and contributes to groundwater protection by limiting vertical fluid migration between permeable geological layers intersected by the borehole. In this context, the present study presents a laboratory-based experimental program aimed at evaluating the thermal and mechanical performance of water-based grout mixtures composed of mineral binders and clay additives (bentonite), with controlled variation of the granular fraction (sand) and bentonite content. The research investigates the relationships between material composition, microstructural characteristics and the physical-mechanical properties relevant for geothermal applications. The experimental methodology includes the determination of thermal conductivity, saturated hydraulic permeability, uniaxial compressive strength and shrinkage or segregation behaviour, complemented by the analysis of rheological characteristics such as injectability and mixture stability under installation conditions. The results highlight the inherent trade-off between enhancing thermal conductivity through the introduction of granular materials and maintaining effective hydraulic sealing by reducing permeability and controlling pore structure. The findings contribute to the development of technical recommendations for optimizing grout formulations used in geothermal boreholes, with the aim of improving heat transfer efficiency, ensuring mechanical integrity and protecting groundwater resources in geothermal systems designed for nearly zero-energy buildings (NZEB).

Key words*: environmental sustainability, grouting materials, nearly zero-energy buildings (nzeb), thermal conductivity.*

INTRODUCTION

The transition towards low-carbon and energy-efficient buildings has increased interest in shallow geothermal energy systems as reliable renewable technologies for heating and cooling applications. Ground source heat pump (GSHP) systems are recognised as effective solutions for reducing primary energy consumption and greenhouse gas emissions while supporting building decarbonisation strategies (Lund & Toth, 2020; Mahmoud et al., 2021).

Vertical borehole heat exchangers (BHEs) are widely used in densely urbanised areas where available land is limited. The thermal performance of these systems depends on the combined properties of the geological formation, the heat exchanger pipes and the material filling the annular space between the pipes and the borehole wall (Spitler & Gehlin, 2015; Albers et al., 2024).

The annular backfill material, commonly referred to as grout, performs multiple functions within a geothermal borehole. In addition to providing mechanical stability and hydraulic sealing, grout establishes thermal contact between the heat exchanger and the surrounding ground, thereby influencing borehole thermal resistance and overall system efficiency (IEEE Standards Association, 2017; Albers et al., 2024). Consequently, geothermal grout design requires balancing thermal conductivity, hydraulic performance and mechanical strength.

Commercial geothermal grouts are typically composed of cement, bentonite and mineral aggregates. Previous studies have shown that increasing the proportion of thermally

conductive granular materials, particularly quartz sand, can improve heat transfer efficiency, whereas higher bentonite contents generally enhance sealing performance but may reduce thermal conductivity (Borinaga-Treviño et al., 2013; Mahmoud et al., 2021; Mascarin et al., 2022; Nakládal et al., 2024).

In this context, the experimental evaluation of geothermal grout formulations remains essential for identifying compositions capable of simultaneously providing efficient heat transfer, low permeability and adequate mechanical strength. The present study investigates fourteen grout formulations containing different proportions of cement, bentonite and quartz sand in order to evaluate the relationships between composition, thermal conductivity, hydraulic permeability and uniaxial compressive strength. The results contribute to the identification of compositional trends governing the trade-off between thermal performance, sealing capacity and mechanical resistance in geothermal grouting materials.

GEOTHERMAL DRILLING TECHNOLOGY

Closed-loop shallow geothermal systems provide an efficient solution for harnessing thermal energy from the subsurface and are widely used in residential, commercial, and industrial applications. Heat transfer is achieved through a closed hydraulic circuit in which the heat transfer fluid circulates in buried pipes without direct interaction with groundwater, thereby reducing hydrogeological risks and ensuring stable long-term operation (Borinaga-Treviño et al., 2013).

The most common configuration is represented by vertical borehole heat exchangers (BHEs), which are constructed through boreholes typically 50 to 200 m deep, with high-density polyethylene (HDPE) pipes installed in a double U-tube configuration. The circulating heat transfer fluid exchanges heat with the surrounding ground, taking advantage of the thermal stability of the subsurface (Spitler & Gehlin, 2015).

A key component of the system is the material used to fill the annular space between the borehole wall and the pipes, known as the grout. This material directly influences the thermal resistance of the borehole and plays a dual role in providing mechanical stability and hydraulic sealing, as well as providing effective thermal coupling between the heat exchanger and the surrounding ground. Consequently, the thermal and structural properties of the grout are critical to the overall efficiency of the system (Albers et al., 2024).

From a design perspective, the thermal performance of a geothermal borehole is determined by the total thermal resistance of the system, which includes contributions from the surrounding ground, pipes, and grout. Reducing the thermal resistance of the grout layer is therefore a key objective in improving system efficiency.

At the same time, the grout must have low permeability to prevent vertical migration of groundwater, which requires careful optimization of the material composition (Spitler & Gehlin, 2015; IEEE, 2017).

The design and construction of geothermal wells must take into account the local geological and hydrogeological conditions, including the thermal conductivity of the ground, the stratigraphic structure, the presence of groundwater, and the stability of the borehole walls. These factors affect both the technical feasibility and the long-term performance of the system.

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MATERIALS AND METHODS

Standardized sand was used for sample preparation in accordance with EN 196-1:2016, which specifies the particle size distribution for cement mortars. The particle size distribution corresponds to that defined in Table 1 of the standard, without using alternative gradations, in order to ensure the repeatability of the test and to isolate the influence of the active components in the presence of water.

The hydraulic binder used consisted of high early strength Portland cement (CEM II/A 42.5R) and sodium bentonite. The mixing water was potable water used under controlled laboratory conditions.

Unlike conventional grout studies based on a constant aggregate-to-binder ratio, the present experimental program intentionally varied the proportions of quartz sand, cement and bentonite in order to evaluate their influence on thermal conductivity, hydraulic permeability and mechanical strength across a broad compositional domain representative of geothermal grouting materials.

Sand acts as an inert component and does not participate in hydration processes. Its primary function is to provide structural stability to the material and to facilitate heat transfer through solid-solid contact. By maintaining a constant sand content, the influence of the interaction between cement and bentonite on the material behaviour can be clearly evaluated.

Table 1. Composition of the grout formulations analyzed

Grout mix	w/s [-]	Sand [%]	Cement [%]	Bentonite [%]
R1	1.82	40	45	15
R2	1.23	9	55	36
R3	0.91	18	50	32
R4	0.82	27	45	27
R5	0.68	36	41	23
R6	0.59	45	36	18
R7	1.64	80	10	10
R8	0.50	70	20	10
R9	0.50	70	15	15
R10	0.65	70	10	20
R11	0.35	70	25	5
R12	0.56	65	20	15
R13	0.60	65	15	20
R14	0.60	65	25	10

The investigated formulations were designed to cover a broad compositional domain representative of geothermal grouting materials used in borehole heat exchanger applications. The experimental matrix was intentionally developed to explore the interactions between three functional constituents: cement, responsible for mechanical integrity; bentonite, responsible for hydraulic sealing and mixture stability; and quartz sand, acting as a thermally conductive granular skeleton. The selected formulations do not represent optimized commercial products but experimental compositions covering low, intermediate and high contents of each component in order to identify the relationships between composition, thermal conductivity, permeability and compressive strength.

Formulation R7, characterized by an unusually high sand content (80%), was intentionally included as a boundary composition to investigate the maximum thermal conductivity that could be achieved within the tested material system. Although such compositions may present practical limitations regarding injectability and field applicability, they provide valuable information regarding the upper thermal performance limit associated with granular enrichment.

Mix preparation

The mixes were prepared under laboratory conditions using a methodology closely related to field practice. In contrast to procedures involving prehydration of bentonite, all dry components (sand, cement and bentonite) were mixed first and then water was added.

This approach makes it possible to reproduce real-life conditions and reduce preparation time, while maintaining an adequate level of mix homogeneity.

The fresh mix was poured into cylindrical plastic molds with a diameter of 50 mm and a height of 100 mm. The specimens were saturated and tested after 28 days to ensure full development of mechanical properties.

Thermal test procedure

The thermal properties of grout materials were determined using the transient line source (TLS) thermal needle method, which is widely used to measure the thermal resistivity and thermal conductivity of soils and geothermal well pack materials. This technique is standardized by IEEE Std 442™-2017 and ASTM D5334 (IEEE, 2017; ASTM D5334, 2022).

The method is based on the application of a controlled thermal pulse generated by a linear probe that functions simultaneously as a heat source and a temperature sensor. The temperature rise recorded over time is used to determine thermal properties through analytical modeling based on the theory of transient heat diffusion.

Thermal resistivity (ρ) is calculated using the following relationship:

$$\rho = \frac{4\pi(T_2 - T_1)}{q \cdot \ln\left(\frac{t_2}{t_1}\right)}$$

where T_1 and T_2 are the temperatures measured at times t_1 and t_2, respectively, and q represents the heat input per unit length.

To ensure the accuracy of the results, the data were filtered to exclude time intervals characterized by non-linear behaviour, associated with transient and boundary effects. The analysis was performed by plotting the temperature as a function of the logarithm of time, taking into account only the linear part of the curve.

The following relationship was used to determine the thermal conductivity:

$$\lambda = \frac{1}{\rho}$$

For each sample, a controlled pre-drilling was performed to allow the insertion of the thermal probe, ensuring uniform contact between the probe and the material.

Mechanical and hydraulic testing

The permeability coefficient was determined using the constant head permeameter method, which is suitable for low permeability materials.

The uniaxial compressive strength was determined according to EN ISO 17892-7:2018 using standard cylindrical specimens.

For each grout formulation, three independent determinations were made for each type of test and the values reported represent the arithmetic mean of the results, ensuring the reproductibility and statistical reliability of the data.

RESULTS AND DISCUSSIONS

The ternary plots were constructed considering only the solid constituents (sand–cement–bentonite), normalized to 100%. The water-to-solid ratio was treated as an independent parameter and therefore not included in the ternary representation.

Presentation of experimental data

The experimental results obtained for the 14 grout formulations are summarized in Table 2 in relation to the compositions presented in Table 1. The parameters determined include the permeability coefficient (k), the uniaxial compressive strength (Cu), the thermal conductivity (λ) and the thermal resistivity (ρ).

Table 2. Hydromechanical and Thermal Properties of the Formulations Analyzed

Grout mix	k [cm/s]	Cu [kPa]	λ [W/mK]	ρ [mK/W]
R1	1.44E-09	3248	1.292	0.774
R2	6.30E-08	1126	0.914	1.095
R3	4.82E-08	1505	0.966	1.036
R4	2.97E-08	1884	1.012	0.988
R5	2.70E-08	1974	1.105	0.905
R6	1.47E-08	2047	1.201	0.833
R7	1.22E-08	1955	1.901	0.526
R8	3.52E-08	626	1.468	0.681
R9	4.49E-08	786	1.509	0.663
R10	6.51E-08	317	1.413	0.708
R11	3.54E-08	1719	1.744	0.573
R12	8.42E-08	893	1.442	0.694
R13	1.23E-08	744	1.482	0.675
R14	2.97E-08	2000	1.624	0.616

The data show significant variation between formulations, reflecting the influence of composition on material properties. The thermal conductivity ranges from 0.9135 to 1.9005 W/mK, the permeability coefficient from 1.44×10-⁹ to 8.42×10-⁸ cm/s, and the mechanical strength from 316.9 to 3248.2 kPa.

Thermal conductivity

The thermal conductivity values show a wide variation among the mixes analyzed (Figure 1). Higher values are observed for mixes characterized by a higher sand content (e.g. Mix 7), while lower values are associated with mixes containing higher proportions of bentonite (e.g. Mix 2).

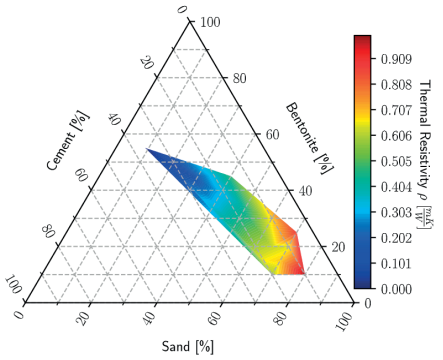


Figure 1. Variation of thermal conductivity for the analysed grout mixes

Permeability

The permeability coefficient varies by about one order of magnitude (Figure 2). The lowest values are associated with mixes containing a higher proportion of fines (cement and bentonite), while higher values are observed in mixes with a predominantly granular structure.

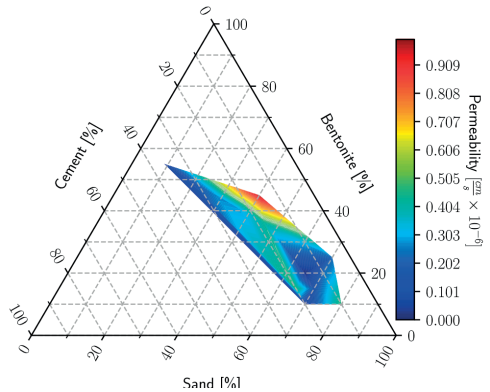


Figure 2. Variation of the coefficient of permeability (logarithmic scale)

Mechanical strength

The uniaxial compressive strength shows significant variation among the mixes analyzed (Figure 3). The highest values are recorded for mixes with higher cement content (e.g. Mix 1), while the lowest values correspond to mixes with reduced binder content.

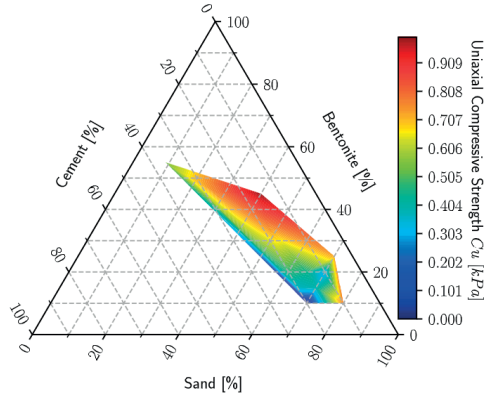


Figure 3. Variation of uniaxial compressive strength

Thermal conductivity–permeability relationship is presented in Figure 4.

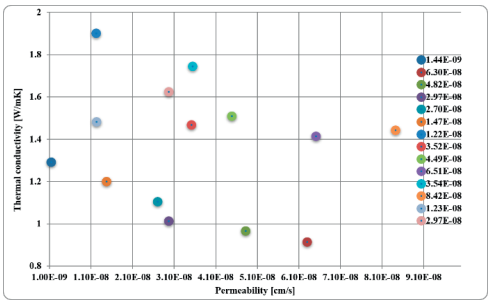


Figure 4. Relationship between thermal conductivity and permeability

The comparative analysis shows simultaneous variations in thermal conductivity and permeability among the analyzed mixes, suggesting that composition has a direct influence on both parameters.

CONCLUSIONS

The experimental investigation of fourteen geothermal grout formulations demonstrated that the thermal, hydraulic and mechanical behaviour of grouting materials is strongly influenced by the relative proportions of quartz sand, cement and bentonite.

Thermal conductivity increased with increasing sand content, reaching a maximum value of 1.901 W/mK for formulation R7, while higher bentonite contents generally reduced thermal performance. Conversely, increasing the proportions of cement and bentonite improved hydraulic sealing by reducing permeability and contributed to the development of a more mechanically stable matrix.

The results confirm that thermal conductivity, permeability and compressive strength are governed by different physical mechanisms and cannot be simultaneously maximised. Consequently, geothermal grout design requires balancing thermal performance, hydraulic sealing capacity and mechanical resistance.

The ternary analysis provided a useful representation of the investigated compositional domain and enabled the identification of performance trends across the sand–cement–bentonite system. Higher sand contents were associated with improved thermal conductivity, whereas higher cement

and bentonite contents promoted lower permeability and greater mechanical stability.

Overall, the investigated formulations should be regarded as a compositional framework for evaluating performance trade-offs rather than as isolated mixtures. In particular, formulation R7 represents a boundary composition defining the upper thermal conductivity limit of the investigated system.

Future research should focus on the incorporation of thermally conductive additives and industrial by-products, long-term durability under thermal cycling, and the coupled thermo-hydro-mechanical behaviour of geothermal grouts under representative operating conditions.

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