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A review of grout materials in geothermal energy applications

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ABSTRACT

Ground heat exchangers are surrounded by grout material, making it one of the most important components in geothermal energy applications since it significantly affects the system's thermal performance. The current study reviews the different types of grout materials and compares their thermophysical properties. The most critical parameter is the grout's thermal conductivity in which it always presents a proportional relation with the system's efficiency. Numerous factors are involved in this review to ascertain theier impact on the grouts' performance such as flowability, shrinkage, moisture content, freezing, heat capacity, strength, permeability, solubility and thermal imbalance. The different grouts compared are bentonite, cement, sand, graphite, controlled low-strength material, dolomite, and phase change materials. The literature shows that phase change materials are the best choices of grouting since they can provide high storage capacity, stability and temperature uniformity. The major problem of such materials is their low thermal conductivity. Thus, it is recommended to use composite phase change materials to enhance their thermal conductivity and increase the storage/retrieval rate.

1. Introduction

The development of systems incorporating renewable energy sources (RESs) is a growing field of research nowadays, targeting the reduction in pollution which results from the burning of fossil fuels [1]. Recently, geothermal energy (GE) is considered as one of the most attracting RESs due to its stability compared to other sources such as wind and solar. Latter sources are characterized by stochastic and intermittent natures, while GE is almost independent of ambient changes (depending on the installation depth). This source can be used to absorb and release heat in energy-related systems. There are several types of GE systems such as ground source heat pump (GSHP) [2], earth-air heat exchanger (EAHE) [3], borehole thermal energy storage (TES) [4] and geothermal power plant (GPP) [5]. Ground-coupled heat exchangers have helped in improving heating, ventilating, and air conditioning (HVAC) systems such that the GSHP and EAHE have been frequently used as air-source heat pump alternatives. These two are classified as shallow GE systems since they are based on installing a ground heat exchanger (GHE). The second type of GE is the deep system which utilizes the heat available in the geothermal fluid and is mostly used for activating GPPs. Several conventional power plants were also retrofitted by adopting GPPs and especially in countries rich in GE resources. There are two main types of GPPs: binary [6] and flash cycles [7]. Fig. 1 shows the possible installations of GE systems in addition to the main specifications including advantages and disadvantages. GE is usually considered a low-grade source hence it is the case that another source of energy is required to meet the demand. With the recent focus on adopting eco-friendly systems, favorable sources to be integrated include either other RESs or the wasted heat from other processes [8,9]. Thus, many research studies have been dedicated to improving the related technologies such as heat recovery [10,11] and energy storage systems [12,13]. One of the most attractive modern types of heat recovery techniques is the heat pipe which has recently become a topic of great interest [14,15]. The development of such technologies requires the enhancement of different related parameters: heat exchanger [16,17], heat transfer [18,19], fluid [20,21], flow rate [22,23], channels [24,25], thermal resistance [26,27], and energy storage [28,29].

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Nomenclature

Abbreviations

BHE	borehole heat exchanger
CLSM	controlled low-strength material
EAHE	earth-air heat exchanger
GE	geothermal energy
GHE	ground heat exchanger
GPP	geothermal power plant
GSHP	ground source heat pump
HVAC	heating, ventilating, and air conditioning
MPCM	microencapsulated phase change material
PCM	phase change material
RES	renewable energy source
TES	thermal energy storage
TRT	thermal response test

The major barrier facing GE systems is the capital cost and especially when using the vertical-type configuration and deep systems. Shallow GHEs are installed in borehole heat exchangers (BHEs) [30] which are composed of pipes and grout material, as shown in Fig. 2. Grout material is an intermediate medium between the GHE and the soil [31]. It is a critical component in the BHE and known as backfilled material. Grout plays a significant role in providing the appropriate heat transfer rate conditions to achieve the required thermal performance. Thus, the aim of selecting the suitable grout material is to enhance heat transfer between the ground and working fluid to increase the efficiency of the BHE. The thermal properties of the ground must also be investigated before installation which is usually done by the help of a thermal response test (TRT).

Thermal conductivity and heat capacity are the most critical parameters affecting the performance of the BHE [32]. There are mainly three types of GHEs: vertical [33], horizontal [34], and coiled [35]. In all types, the grout's thermal conductivity is almost proportional to the BHE's effectiveness. Sliwa and Rosen [36] compared the single U-tube, double U-tube, and co-axial vertical GHEs to ascertain the grout's heat transfer's effect on the effective heat transfer coefficient of the BHE. The results showed that the grout's thermal conductivity has almost the same influence in all cases regarding the effective heat transfer coefficient.

The current research study presents a review of the different types of grout materials involving cement, bentonite, sand, graphite, dolomite, controlled low-strength material (CLSM) and phase change materials (PCM). These are divided into categories: conventional grouts, additives, and latest versions. The most important parameters affecting the performance and cost of the GE system are presented to find out the optimal grout material that can be used in each specific case. These include the amount of moisture, heat capacity, thermal conductivity, grout mix, permeability, porosity, mechanical strength, shrinkage, flowability and freezing effect.

2. Grouting

During the installation of GHE, a gap is created between the pipes and ground. Thus, a backfilled material is inserted to fill the space inside the BHE. The objective of this material is not only to fill the gaps; while it is also used to provide a convenient medium for heat transfer and avoid pipes' damaging. It is usually recommended to use particles having small sizes to increase the heat capacity of the grout. However, it is essential to avoid affecting the thermal conductivity of the selected material. Clay, silt and coarse are the commonly used grout sizes. Selecting the suitable size is important to reduce the need for constructing long boreholes because the length of BHE depends on the choice of grout material. For example, as the thermal conductivity of the grout increases, the required length of borehole length decreases. Fig. 3 presents the most common types of grout materials that could be used in GE applications.

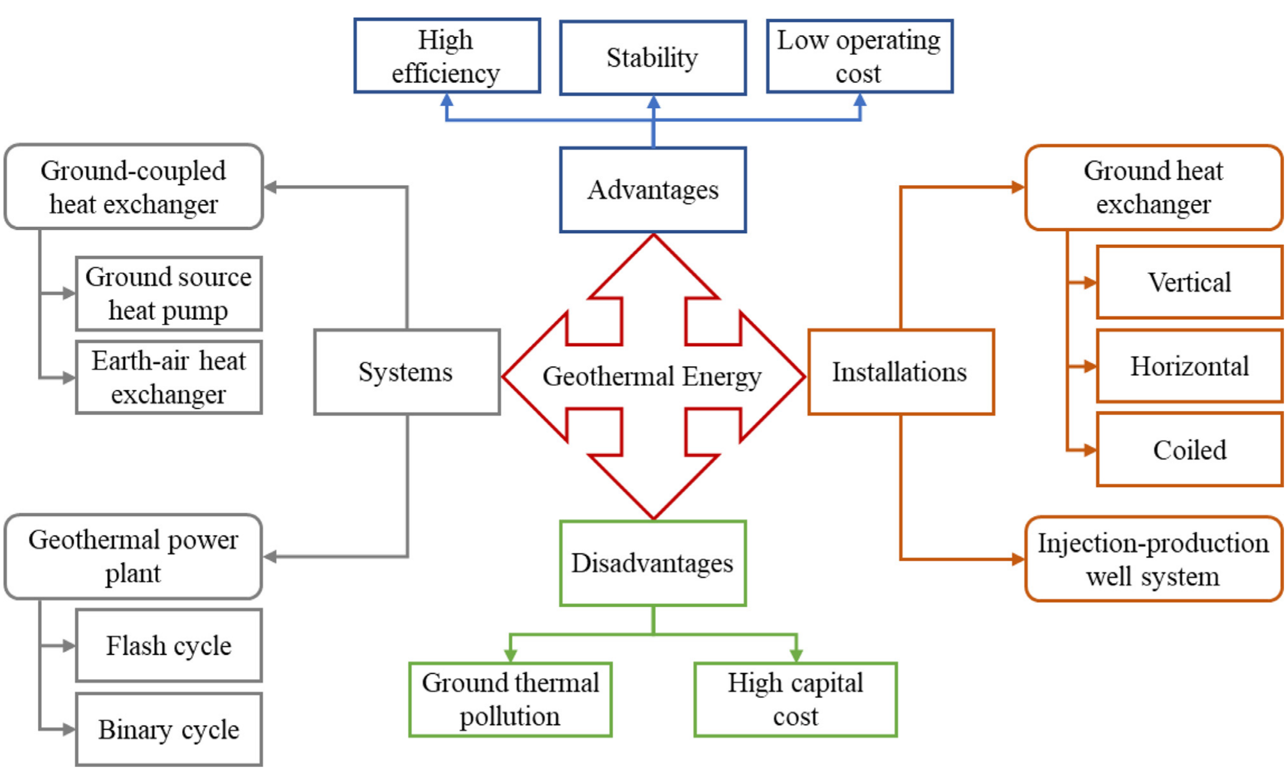

Fig. 1. The utilizations and characteristics of geothermal energy systems.

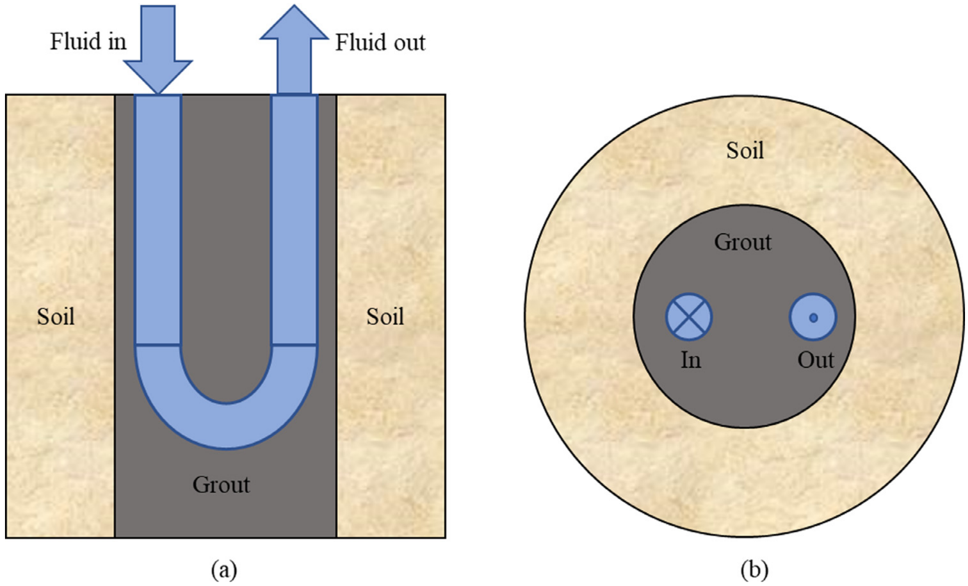

Fig. 2. Borehole heat exchanger; (a) side view and (b) cross-sectional view.

2.1. Conventional grout materials

Bentonite and cement are conventional types of grout materials used in BHEs. Table 1 presents a comparison between these materials in terms of thermal conductivity and thermal resistance. It can also be seen that these parameters are affected by the load, spacers and grout's thickness. The flexibility of bentonite makes it a good sealant to be used in GE and water well systems. Common types of bentonite used are sodium, calcium, and potassium. It is considered as one of the best fluid barriers due to its low permeability preventing fluids from passing easily. In many cases, bentonite is mixed with other materials forming a grout mix aiming to enhance the thermal conductivity. Cement, water, sand, and graphite are the commonly used bentonite additives. Pahud and Matthey [37] compared different types of grout mixtures to conclude that sand and quartz mixture has the lowest thermal resistance amongst the grouts studied. The grout-based materials compared were bentonite, cement, and quartz. The study was performed by applying TRTs on six different boreholes in which the double U-pipe was used as GHE. Bentonite-based grouts were also compared by Lee *et al.* [38] to ascertain the effect of viscosity and salinity on thermal performance of the grout materials. After applying experimental testing, the authors deduced that the interaction between bentonite and salinity can cause significant volume reductions. This was considered a crucial factor leading to an incomplete borehole filling, which can negatively affect the GHE's performance. Apart from that, there are also some other parameters that can inhibit the complete backfilling of BHEs such as density and viscosity differences.

The second type of conventional grout materials used in GE systems is cement. It could be found in several types; however, the commonly used cement-based grout is the Portland cement. It was compared with gravel by Choi and Ooka [39] such that the first grout

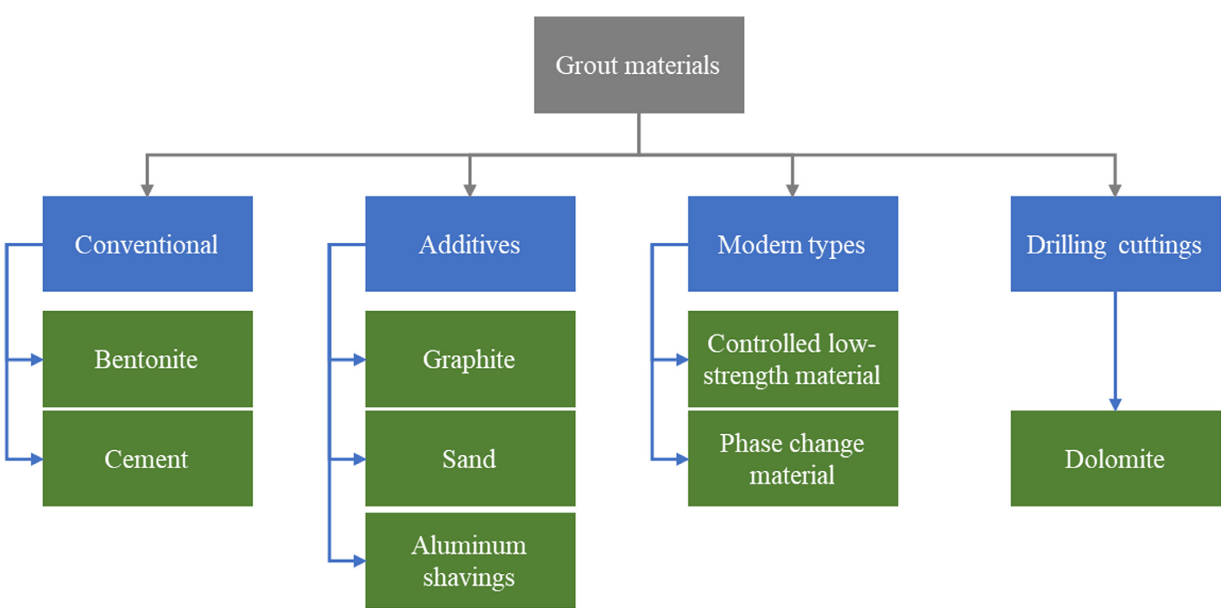

Fig. 3. Commonly used grout materials in geothermal energy systems.

Table 1
Comparison between the conventional grout materials; bentonite and cement.

Reference	Borehole heat exchanger	Effective thermal conductivity (W/m.K)	Calculated thermal resistance (m.K/W)
Pahud and Matthey [37]	13 cm bentonite without spacers	0.7	0.240
	13 cm bentonite with spacers	0.7	0.142
	12 cm bentonite without spacers	0.7	0.150
	12 cm bentonite with spacers	0.7	0.223
Choi and Ooka [39]	Cement (2 kW heater TRT)	1.962	0.159
	Cement (4 kW heater TRT)	2.076	0.155

was formed of cement and 20% of silica sand while the second was formed of gravel with a grain size of 8-15 mm. The results showed that the borehole thermal resistance was higher in the case of cement and needed more time to be backfilled compared to that of gravel. The rate of heat injection was also considered as an important parameter in which it was varying between 45 W/m and 90 W/m. The authors reported that the heat injection rate has a more significant effect than the type of grout on the BHE's thermal performance. This change in heat injection improved the thermal performance in case of cement and gravel by 8.7% and 9.8%, respectively. Borinaga-Treviño *et al.* [40] compared the different types of cement-based grout materials and aggregates to investigate the corresponding thermal conductivities, water content and mechanical properties. Silica sand showed the highest thermal conductivity compared to pure cement and other tested aggregate materials such as limestone sand, electric arc furnace slag, construction waste and demolition waste. The authors also studied the differences between natural and recycled materials considering the replacement of bentonite by cement as a grout-based material in the BHE. Different types of mortars and aggregates were compared in which water, cement and plasticizer were used as mortars while the aggregates were formed of construction/demolishing waste, electric arc furnace slag, silica, and limestone.

2.2. Additives

The thermal resistance of the BHE depends on the characteristics of its components: pipes, grout material, and soil. The components' performances depend significantly on each other such that any change in one of them may affect the other two. For example, if the ground is poor in terms of moisture, it is necessary to choose a grout with high thermal conductivity to enhance the heat transfer rate between soil and GHE. However, conventional grouts cannot offer such high thermal conductivities, making it essential to introduce grout mixtures. Usually, as the grout thermal conductivity increases, the borehole thermal resistance decreases, resulting in a better thermal performance. Endeavors have focused on investigating several types of grout mixtures and compared them to conventional materials as shown in Table 2. Aluminum shavings and sulpho-aluminate cement were studied by Blazquez *et al.* [41] to improve the thermal conductivity of sand-based grout. The results showed that these materials can be used as additives since they have good thermal conductivity and mechanical properties. It was deduced that saturated sand-aluminum shavings and aluminum cement-sand have the highest thermal conductivities. Among the compared materials, the grout mixture that corresponded to the lowest thermal conductivity was formed of bentonite and superplasticizer. Material shavings are usually characterized by their small sizes in which this helps achieving almost uniform distribution.

Graphite is one of the most used additives that have been integrated into conventional grout materials to improve the thermal performance due to its stability regarding its carbon content. The graphite's contribution to the thermo-physical properties of grouts was studied by Erol and François [42]. Graphite was better introduced as an additive and not as grout-based material because when pure graphite was used the performance of the BHE decreased. Additionally, the flowability and strength were negatively affected in the presence of large amounts of graphite. Thus, the authors found that a 5% of graphite would be the best percentage resulting in the highest grout enhancement. The graphite content was further studied by Delaleux *et al.* [43] to enhance the grout material's thermal conductivity. The study aimed to use a percentage of compressed natural graphite less 10%. The results showed that the overall heat transfer could be 1.5 times enhanced while using 5% of graphite in the mixture. This was obtained considering other important factors such as the particle's size and amount of moisture in the grout. Graphite is usually found in two different forms: flake and expanded. Both are formed of high percentages of natural graphite in which the former and latter correspond to values above 94% and 99%, respectively [44]. Expanded graphite is more used as grout additive than the flake-type due to its high surface area and sealing properties. The expanded type is manufactured by passing through an oxidation reaction and

Table 2
The effect of introducing additives into grout materials.

Reference	Grout	Additive	Additive percentage/ratio	Thermal conductivity (W/m.K)
Blazquez *et al.* [41]	Sand	Aluminum shavings	0.5%	3.270
			2%	3.752
			3.5%	3.620
Erol and François [42]	Homemade admixture	Graphite	0%	1.5
		Natural graphite	5%	2.3
		Synthetic graphite 150 μm	5%	2.5
Delaleux *et al.* [43]	Bentonite	Graphite	-	1.5
			5%	5
Kim and Oh [45] (Water/Cement ratio = 0.3)	Cement	Sand	S/C = 0	Saturated: 1.06
				Air-dried: 0.79
			S/C = 0.5	Saturated: 1.62
				Air-dried: 1.28
			S/C = 1	Saturated: 1.87
				Air-dried: 1.58

expansion process reaching a ratio of 200-300. Additionally, the important factor that makes graphite a good additive is the insolubility in water. Thus, when it is used as a grout material, there is no risk of contamination even if it interacts with water.

Another commonly used additive is sand, which has been frequently utilized to enhance conventional-based grout materials' performances. Blázquez *et al.* [41] investigated the effect of aluminum shavings' amount on sand-based grout's thermal conductivity. Below 2.5% of aluminum, the grout's thermal conductivity was proportional to the amount of shavings, while the relationship was inverted at higher percentages. The authors deduced that when using high amounts of aluminum shavings, the number of holes will increase, resulting in an increase in the grout's thermal resistance. It was also expected that these results would change at different amounts of moisture. Kim and Oh [45] compared two types of cement-based grouts to ascertain the effect of additives on the thermal conductivity in which water and sand were used as grout additives. The addition of water showed a better performance compared to that of sand, while the change in sand content percentage was more significant. The comparison was carried out, taking into consideration different saturation levels (see Table 2).

2.3. Controlled low-strength material

CLSM is a concrete mix suitable for backfilling applications such as BHEs in which it is characterized by low strength, good flowability, low shrinkage and high thermal conductivity [46]. Natural sand and marine dredged soil mixture were integrated into CLSM-based grout by Do *et al.* [47]. The aim was to reduce the grout material's bleeding rate to decrease the geothermal system's capital cost. The studied mixture's thermal conductivity was suitable for BHEs such that it was varying between 1.4 W/m.K and 1.82 W/m.K. The commonly used CLSM types are composed of fine aggregates, cement, fly ash, and water. Usually, sand and coal are used as fine aggregates. The heat exchange rate in the BHE was investigated by Do *et al.* [48] while comparing different CLSM mixtures with conventional grout materials. The composition ratio of CLSM was also varied to select the optimal material and study its effect on the total cost. The results showed that the incorporation of all CLSM types can enhance the GE system's performance regarding the thermal properties and economical aspect. Two types of GHEs were involved in the mentioned study that are the U-type and spiral-type. The geothermal system's total construction cost was reduced by 20.8% in a study performed by Kim *et al.* [49] while using a by-product-based CLSM with bentonite-sand mixture. Quartz-based mine tailings and pond ash were used as fillers and aggregates, respectively. Pond ash was introduced as an alternative to natural sand. The aim was to enhance the mechanical strength of CLSM. Quartz-based mine tailings and pond ash are usually formed of SiO_2, AL_2O_3, Fe_2O_3, CaO, MgO, MnO, Na_2O, K_2O, TiO_2 and P_2O_5. The difference between the two materials (quartz and pond ash) is the ratio of each chemical substance. The addition of such materials into CLSMs must be based on compromising between the mechanical and thermal properties because this addition may be accompanied by a decrease in grout's thermal conductivity. The thermal conductivity of CLSMs can be further enhanced by decreasing the fineness modulus as reported by Do *et al.* [50]. This was deduced while comparing the excavated soil and pond ash in CLSM mixtures.

2.4. Dolomite

Calcium magnesium carbonate rock is known as dolomite and can be used as a backfill material in boreholes to reduce the GE system's installation capital cost. Dolomite drilling cuttings were investigated by Luo *et al.* *[51]* and compared with bentonite and cement mixtures. The application was based on a GSHP in which a TRT was carried out to study the system's heat transfer performance and economic feasibility. The reduction in cost using dolomite drilling cuttings was significant compared to that of concrete and bentonite-quartz. The corresponding reductions were 14.87% and 17.16%, respectively. The geological profile of the BHE studied was formed of several layers of dolomite drilling cuttings with a total depth of 100 m. The thickness of each layer depends on the characteristics of ground and grout. The shallower layer was backfilled with 2.5 m of gravel and clay while the deeper layers were backfilled with dolomite. As for bentonite-based grout, the optimal mixture ratio of dolomite to bentonite was 2 to 8 and the thermal conductivity of this mixture was 1.96 W/m.K. The thermal conductivity was higher in case of using cement mixture in which the value was 2.19 W/m.K considering an optimal dolomite to cement mixture ratio of 3 to 7.

2.5. Phase change materials

There are two main types of TES systems that are the sensible and latent [52]. Several types of sensible storage materials can be used to store/release heat such as water, rock, oil, carbonate salt, steel, and concrete. These materials store and release heat by increasing and decreasing their temperature, respectively [53,54]. However, latent storage materials store/release energy by changing their phase and can be found in the form of inorganic, organic and eutectics [55,56]. The most used PCM is the paraffin wax which has been introduced into several types of applications [57,58]. The use of PCM has increased considerably recently due to its various advantages compared to sensible materials [59]. The most important factors that characterize latent TES systems are the high heat capacity and stability. The high capacity of PCM facilitates the reduction in required TES tank volume. These materials almost operate at constant temperatures which can make the energy systems more stable, while the phase change temperature must be chosen precisely based on the system's operating conditions. PCM can be used in all types of energy systems such as heating, cooling, and power generation. For example, it can be added as an insulation in HVAC systems [60,61]. Also, PCM help in increasing the penetration of solar energy which can be done by storing the excess of energy to overcome the stochastic and intermittent nature of solar energy [62,63]. PCM has an important role in enhancing heat recovery techniques to retrofit existing energy-related systems [64]. The major problem of such materials is the low thermal conductivity compared to the other storage materials. Thus, they are mostly used in long-term storage applications. Many studies have been dedicated to improving the thermal performance of PCM. It was found that several types of materials could be introduced to increase the heat transfer rate such as water, copper, metal foam and expanded graphite.

In shallow GE systems, thermal pollution is one of the most critical problems that may occur. This could be found in the form of heat accumulation and thermal depletion in the case of cooling and heating, respectively [65]. Thus, PCM can be incorporated as grout materials to increase the capacity and reduce the effect of high peak loads (see Table 3 and Fig. 4). Even under normal conditions, the addition of PCM can reduce the total volume of installation and, hence, decrease the capital cost. This encourages to use horizontal and shallow GHEs instead of vertical and deep systems. Another factor that helps to reduce the volume of installation is the low soil thermal interference radius which can decrease the required space between the GHE's pipes. The soil thermal interference radius can be reduced by 13% using PCM instead of soil backfill as reported by Yang *et al.* [66]. Kong *et al.* [67] investigated the use of microencapsulated phase change materials (MPCM) to improve the coefficient of performance of a GSHP in which it was enhanced up to 4. PCM can also decrease the outlet temperature fluctuations of EAHEs. Liu *et al.* [68] compared the use of PCM in the EAHE and traditional system to show that the temperature fluctuations can be reduced up to 31%. PCM can also be

Table 3
Summary of the phase change materials presented as grouts in the current review paper.

Reference	Phase change material	Phase change temperature (°C)	Thermal conductivity (W/m.K)	Density (kg/m^3)	Latent heat (kJ/kg)
Yang *et al.* [66]	66% decyl acid & 44% lauric acid	20.55	0.235	880	133.7
	Oleic acid	8.11	0.330	881	94.5
Kong *et al.* [67]	MPCM (methyl stearate & polyurea)	36.90–41.70	0.559–0.589	975–983	9.0–20.9
Liu *et al.* [68]	RT-22	~22	0.21	779–870	133.4–165.5

used as a TES tank to store energy excess, especially in hybrid systems incorporating GE and solar energy [69].

3. Grout material testing

Grout materials should always be tested before being installed to check if the thermal and mechanical properties are suitable for the BHE in terms of performance and structure. The test used more commonly is the durability test which consists of various wet and dry cycles. The test starts by placing the material in a water tank for approximately a day. Then, it should be dried in ambient conditions for two days. After that, the thermal performance and mechanical strength must be measured and compared to the initial values. The properties that are usually taken into consideration in such tests are the thermal conductivity, compressive strength, and flexural strength. This test was further enhanced by Indacoechea-Vega [70] in which it was recommended to apply freeze-thaw cycles in addition to the wet-dry cycles. This test is known as the double durability test and is mainly used to determine the optimal water to grout ratio which significantly affects the freezing status. This ratio depends on the type of grout material and amount of heat addition/rejection. It is also essential to examine the grout material before installation to avoid contamination which may occur due to underground chemical reactions. Contamination may cause failure in the system's operation or a decrease in its performance. It is better to use additional amounts of water at high loads as reported by Indacoechea-Vega *et al.* [70] since this will increase the workability of grout. It was also mentioned that a high amount of water is preferable in the presence of stability and when the system is thermally balanced. In some cases, it would be necessary to use another source of energy to compensate the average heat/coolth lost which usually occurs at high loads. Thus, hybrid geothermal systems are considered as a solution for thermal imbalance. The type of geothermal hybrid most often used is the solar-geothermal system [71]. However, solar energy's stochastic and intermittent nature make it crucial to integrate fast response energy storage systems [72]. Such combinations are frequently used in remote islands and microgrid district energy systems [73].

4. Moisture content

One of the most important factors affecting the heat transfer rate in grout materials is the degree of saturation which represents the amount of moisture in grout. This was confirmed by Kim and Oh [45] in which the change in amount of moisture significantly affected the thermal conductivity and specific heat capacity of the grout material. The results showed that the relation between degree of saturation with both properties was directly proportional. The same result was achieved by Do *et al.* [50] in which the CLSM was used as grout. Kim *et al.* [32] mentioned that this relation will be reversed after reaching the degree of saturation. This means that the amount of water in the grout must not be increased at high degrees of saturation. Some important factors may change the degree of saturation's effect, such

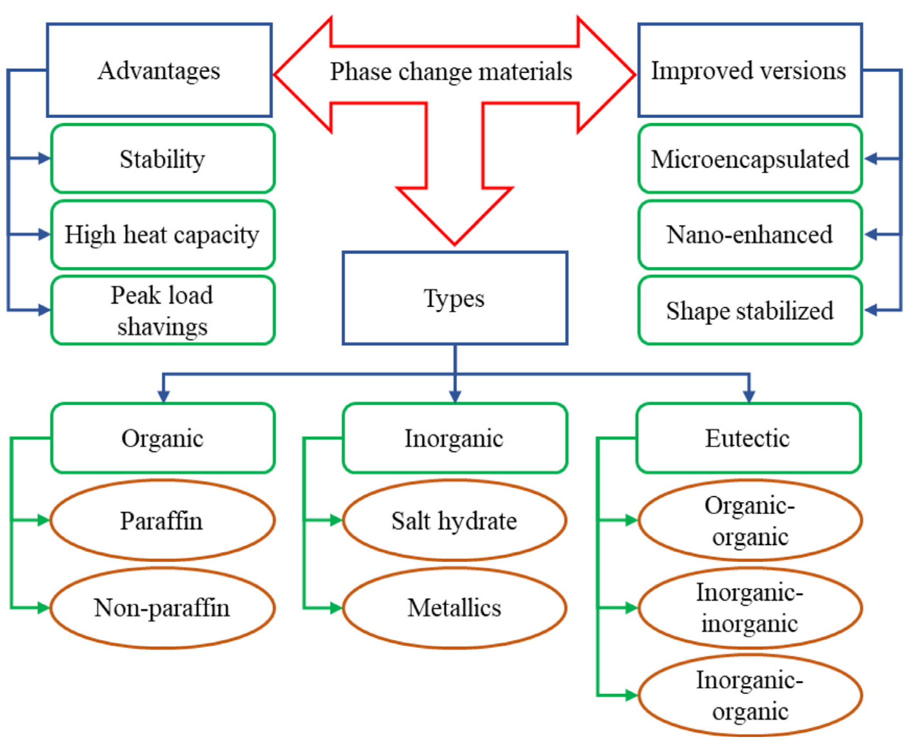

Fig. 4. Phase change materials; advantages, types and improved versions.

Table 4
Advantages/disadvantages of the grout materials reviewed in the current paper.

Grout material	Advantages	Disadvantages
Bentonite		
	3- Flexibility	3- Low thermal conductivity
	3- Low permeability	3- Volume reductions
Cement	High strength	Low thermal conductivity
Graphite		
	3- High thermal conductivity	3- Low flowability
	3- Insoluble in water	3- Low strength
Dolomite	Low cost	Fragile
Controlled low-strength material		Low strength
	3- Good flowability	
	3- Low shrinkage	
		3- Low thermal conductivity
Phase change materials	High capacity	
		3- Leakage

as mixture ratio [74] and matric suction [50]. The latter represents the pressure exerted by the dry material on the surrounding to equalize the water content. Do *et al.* [50] deduced that the relationship between matric suction and degree of saturation is independent of mixture proportions and do not present a linear relation such that when the matric suction was less than 100 kPa, the degree of saturation decreased slightly. However, at high values of matric suction, the degree of saturation's drop rate was increased.

The risk of using a high degree of saturation needs to be considered as an important factor since it has a significant effect on the grout's freezing which may cause critical damage to the GHE's pipes and grout material. This may occur due to ice formation followed by volume expansion. This would probably happen at high heating loads. In such cases, it is recommended to use anti-freeze mixture (low freezing point). In some applications, the GHE is installed underneath the building. This can also increase the risk of freezing which may cause a damage in the building's foundation after a certain time [75]. In the absence of heat compensation, the freezing can expand under the ground and cause severe damages. Additionally, some other factors can influence the freezing effect, such as soil/grout's permeability and porosity. Erol and Francois [76] suggested using a grout material having a thermal conductivity almost equal to that of the surrounding soil to avoid freezing. The results also showed that the grout materials having low permeability and high porosity may be fractured when applying the freezing test.

5. Discussion

Grout material plays a crucial role in the performance of GE systems. It must be selected precisely whilst balancing between the thermal and mechanical properties. The grout is an intermediate medium between the ground and GHE. Thus, it must provide convenient conditions for heat transfer as well as protecting the GHE from being damaged when subjected to external pressure. Bentonite and cement have been considered as conventional grout materials and used in many BHE installations previously due to their high strength and low permeability. However, they have exhibited critical issues such as low thermal conductivity and volume reductions. Additionally, their mechanical and thermal properties would change when interacting with water. Modern versions of grout materials integrate different additives into conventional types. One of the most used additives is graphite which can significantly increase the thermal performance of the grout. It can help avoiding chemical reactions from occurring since it is insoluble in water. Besides that, the cost of installation and grout material used need to be taken into consideration. These encourage to use drilling cuttings such as dolomite to reduce the capital cost of BHE, while it is still unsuitable for all cases because it is fragile. Another frequently used grout is the CLSM, which is characterized by its good flowability and low shrinkage. However, such materials' low mechanical strength is also a major problem that necessitates the integration of additional supporting materials. Table 4 presents a summary of the specific properties of the different reviewed grout materials.

Recommendations

The type of grout material can significantly affect the soil thermal interference radius. This parameter is very important in BHEs since it can increase/decrease the capital cost of installation, required borehole length and performance of the GE system. Additionally, the thermal radius cannot be controlled in the absence of heat compensation. This demands the use of modern types of grout materials such as PCM which are mainly characterized by high storage capacity. PCM can provide stability and reduce the risk of thermal imbalance that may occur at high loads and consequently enhancing the GE system's performance. However, many types of PCM do not have adequate heat transfer properties as compared with other materials. In these cases, it would be preferable to use composite [77] and MPCM [78]. Another method to enhance the thermophysical properties of PCM is to incorporate nano particles such as copper. This type of storage material is known as nano-enhanced PCM [79,80]. The second problem of conventional PCM is the risk of leakage [81]. Therefore, shape-stabilized PCM could be used in which they are based on adding a supporting material to ensure stability and avoid leakage. One of the commonly used PCM-based shape-stabilized material is polyethylene glycol [82]. In some applications, the choice of grout material cannot solve the problem of thermal imbalance due to the extreme high loads meaning that GE will not be able to stand alone. In such cases, hybridization would be the best solution to provide additional amount of power when needed. Fig. 5 presents the important parameters that affect the selection of grout materials including risks, positive/negative factors and required assessments.

Grout material selection

Selecting the most suitable grout material is a complex process which needs to be carried out for each specific application depending on the available conditions and characteristics of the GE system. Conventionally, bentonite and cement were the most frequently used types of grout due to their high mechanical strength. The thermal conductivity of these grout materials can be enhanced by using additives such as graphite, aluminum shavings and CLSM. However, all these mentioned materials cannot ensure stable output or avoid thermal imbalance. Thus, PCM is attractive with its high storage capacity

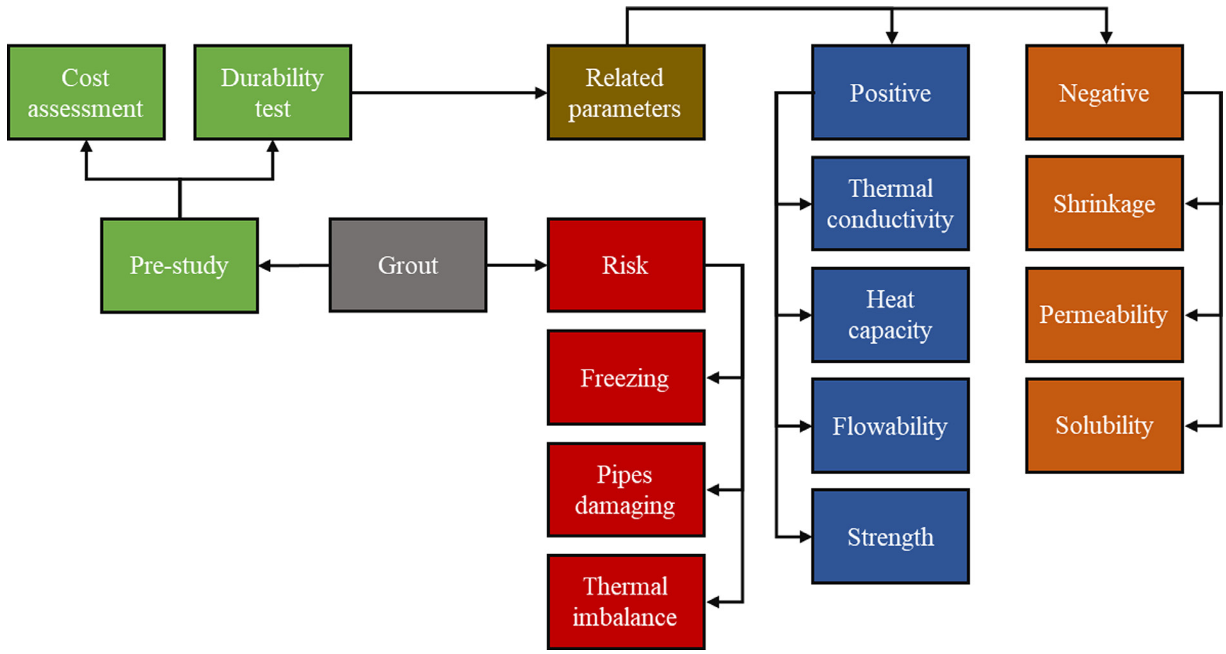

Fig. 5. The factors affecting the selection of grout materials.

and phase change temperatures near to the operating and surrounding temperatures. These characteristics contribute to reduction in soil thermal interference radius and provision of stability. Therefore, grout mixtures must be chosen to create a good balance between the mechanical strength, thermal conductivity and storage capacity of conventional grouts, additives and PCM, respectively.

6. Conclusion

The high capital cost of GE system's installation makes it essential to study the different components of the BHE. The current study highlighted the importance of investigating grout materials whilst presenting the effects of grout properties on system performance. Several types of materials were reviewed such as bentonite, cement, sand, graphite, CLSM and PCM. Each type should pass the durability/ double durability test before being used. This is necessary to ensure the endurance of the selected grout material as well as to study its thermal and mechanical properties. To select the appropriate grout material it is necessary to examine the pressure inside the BHE, inlet/ outlet fluid temperature and load. Bentonite and cement were considered as conventional grouts and had presented almost similar results in the previous reviewed investigations. These materials were previously used since they represent good sealants and have high mechanical strengths. The major barrier facing bentonite and cement is the low thermal conductivity. Thus, sand and graphite can be introduced as additives to enhance the thermal performance of the grout mix. Another factor that can enhance the heat transfer is the degree of saturation. However, after exceeding the full saturation point, the increase in the degree of saturation may be accompanied by negative effects. The GE system's capital cost is directly related to the required size of BHE and the cost of backfilling material. Thus, dolomite drilling cuttings could be used to backfill the BHE to reduce the cost of installation. According to the reviewed literature, CLSM and PCM have been considered as attractive grouts. The former is characterized by low shrinkage and high flowability in which these are suitable properties for grouting. However, the low strength of CLSM makes it inappropriate for standing alone. The latest version of grout material is the PCM in which it provides several advantages regarding capacity and stability mainly. It can reduce the soil thermal interference radius and avoid thermal imbalance which may occur at high load or in cases where there is insufficient heat compensation. Selecting composite PCM is highly recommended, allowing heat transfer between grout and soil/GHE to be optimized. This could be done by integrating additional elements such as water and graphite. Further studies should be dedicated to exploring new composite PCM to be more suitable for BHEs. Such grout materials must be specially prepared to avoid the reduction in PCM's high capacity when enhancing heat transfer by means of high thermal conductive additive materials.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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