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A Review on Thermal Conductivity of Soil and MICP Technique

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ABSTRACT

Thermal conductivity is the fundamental material property that is essential for characterizing heat transfer. It is one of the soil properties that measures the heat transfer that takes place in the soil. This review paper summarises the current state of knowledge on the thermal conductivity of soil, including factors affecting its measurement and variability. It discusses different methods of measuring thermal conductivity, including laboratory techniques and field methods. It also covers the impact of soil properties, such as soil type, moisture content, and temperature, on thermal conductivity. The MICP technique, which uses bacteria to produce calcite within soil, leads to improved thermal conductivity by filling pores and increasing bulk density. The paper provides a comprehensive overview of the research on the use of MICP for improving soil thermal conductivity, including the benefits and limitations of the method. It also explores the relationship between thermal conductivity and other soil properties, such as porosity and bulk density. Furthermore, the paper emphasises the significance of considering soil thermal conductivity in a variety of applications, including building heating and cooling systems, energy storage in soil, and heat transfer in geothermal systems.

Keywords: Thermal conductivity of soil, MICP technique, Guarded hot plate, Energy geostructures, Thermal conductivity models, Steady state method, Transient state method

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INTRODUCTION

The thermal characteristics of soil play a crucial role in various engineering endeavors and situations involving heat exchange in soil. These properties are especially critical in designing infrastructure such as roads, airfields, pipelines, and buildings in cold regions, as well as in underground power cables, hot water pipes, and cold gas pipelines in non-frozen ground. Additionally, they are significant in agriculture, meteorology, and geology [40].There are number of factors which affects the thermal conductivity of soil such as bulk density, moisture content, Organic matter, salt content. As soil moisture and density rose, thermal conductivity increased as well.. It decreases with increase in amount of added salt and percentage of soil organic matter. Sand have higher value of thermal conductivity than clay [38]. When the dry density of soil increases, its thermal conductivity also increases. This is because the increase in density leads to a reduction in air volume and an increase in particle contact, resulting in an increase in soil volume [42]. The extent of particle contact and, consequently, thermal conductivity of granular soil depends on various factors, including particle shape, void ratio, and relative density. To account for the effect of particle shape, the overall irregularity of the soil is considered. As the overall irregularity increases, the void ratio decreases, leading to an increase in thermal conductivity. However, if the void ratio is the same, the particle shape has little impact on the thermal conductivity of granular soil. The thermal conductivity of granular soil increases with increasing relative density at a given overall irregularity. Furthermore, at a given relative density, the thermal conductivity increases with an increase in overall irregularity [54]. Medium textured soils, thermal properties are more strongly correlated with an than with Vs. This is due to increase in air field will decrease the latent heat transfer in the soil at same relative humidity in the pore space [50]. There is an inverse relationship between the thermal conductivity and electrical resistivity of soil, meaning that an increase in the thermal conductivity of soil results in a decrease in its electrical resistivity, and vice versa [48]. After treating soil with Synthetic Root Exudates and distilled water for seven days at 18 °C, the thermal conductivity decreased. This is because the treatment led to an increase in organic matter, which in turn caused a decrease in thermal conductivity [53].

There are various laboratory techniques used to determine the thermal conductivity of soil. These techniques involve either transient heat state or steady state heat flux conditions. Examples of these techniques include the Guarded Hot Plate method, Thermal Needle Probe method, Axial Flow method, Radial Flow method, and 3-technique method [6, 7]. The selection of a particular laboratory method for measuring the thermal conductivity of a material depends on various factors, including the type of material being tested and other relevant considerations [3, 9]. The thermal needle probe method is employed for measuring the thermal conductivity of soil. This involves inserting a temperature measuring and heating element into the soil sample. A known voltage and current are applied, and the rise in temperature over time is recorded. Based on this data, the thermal conductivity of the soil can be determined [6]. The guarded hot plate method for determining the thermal conductivity of a material involves placing the specimen between two plates. Power is supplied to the heater and heat flows axially through the specimen. The temperature difference between the two plates is then measured using thermocouples or thermistors that are attached to the plates[7]. The most commonly used method for measuring the thermal conductivity of soil is the guarded hot plate method. This method can also be used for determining the thermal conductivity of undisturbed samples obtained during routine site investigation. When a block is used instead of a plate, there is no significant difference in the thermal conductivity value obtained using this method [35, 9] .

In order to measure the thermal conductivity of a porous material, a cylindrical specimen is used, and a heater is placed at its center to allow for radial heat flow. For reliable results, a thermocouple should be placed in the mid-section of the specimen [11]. The accuracy of the thermal conductivity value obtained through the guarded hot plate method is affected by the temperature distribution in the specimen. However, this can be eliminated by placing the thermocouple in the appropriate position [25, 6]. In addition to the traditional laboratory methods for measuring soil thermal conductivity, new techniques have been developed, such as the thermal cell and spherical probe. These methods allow for the testing of two soil samples simultaneously and are known to provide reliable results [45, 47].

During the process of measuring thermal conductivity, heat loss may occur which can lead to errors in the measured value of thermal conductivity [24]. When comparing laboratory and in-situ methods for measuring soil thermal conductivity, the needle probe (laboratory method) is faster but yields lower thermal conductivity values. On the other hand, the thermal cell (field method) is more time-consuming but provides more accurate results [26].

To address the limitations of both laboratory and field methods for measuring soil thermal conductivity, researchers have developed theoretical models and correlations. These models utilize empirical and semi-empirical relationships to predict the thermal conductivity of soil in both frozen and unfrozen states [5]. Researchers have employed the GA-BPNN (genetic algorithm optimized back propagation neural network) to assess the thermal conductivity of undisturbed soil based on its moisture content, porosity, and natural density [13]. Air-filled porosity has a greater impact on the thermal conductivity of soil than moisture content [54].

The thermal properties of soil can be influenced by microorganisms that are naturally present or artificially introduced to the soil, which can impact heat transfer. These microorganisms can also be utilized in geotechnical engineering to improve soil properties [28, 52] .The physical properties of soil, particularly moisture content and temperature, have a significant impact on the activity of micro-organisms, which can in turn affect heat transfer and thermal properties of the soil [1,4, 2, 30, 19, 34, 23]. Maintaining the correct moisture content in soil is crucial for the activity of soil microorganisms because it influences processes such as organic matter conversion and mineral detoxification [1].

At high temperatures, the growth of micro-organisms is initially low, but after being incubated for one month, the growth increases [4]. The enzymatic activity of soil and the depth of the sample collection are two other factors that affect the growth of micro-organisms along with temperature. Several studies have shown that different depths of soil can have different types and densities of micro-organisms, leading to variations in their activity and growth. Additionally, the enzymatic activity of soil plays a vital role in providing essential nutrients to micro-organisms, which in turn influence their growth and metabolic activity [2, 30, 19, 34, 32, 22, 23]. The application of cattle manure in soil can improve the enzymatic activity, resulting in an increase in exothermal effects [30, 19], hence to enhance the heat transfer in the soil effective micro-organisms should be selected [34].

There are several techniques available to improve the thermal conductivity of soil. One of these is the Microbial Induced Calcite Precipitation (MICP), which is a sustainable and effective method that can increase the thermal conductivity of sand by 95%, 100%, 107.5%, and 120%. When the MICP process is carried out at Cu = 9.7 and e = 0.5 for 15 cycles, the thermal conductivity can be increased by up to three times compared to untreated samples [58]. When the degree of saturation (Sr) of sand treated with MICP is increased, there is a significant increase in thermal conductivity, up to 250%. However, this increase is not very significant when Sr is less than 0.2. On the other hand, when Sr is greater than 0.2, there is a significant increase in thermal conductivity. This has been observed in various studies [44, 27]. The main reason for the enhancement of thermal conductivity in sand treated with MICP is due to the formation of CaCO3, which creates a "thermal bridge" effect. This micro-mechanism significantly improves the thermal conductivity of sand. Additionally, adding calcium carbonate (CaCl2) can also increase the thermal conductivity of MICP treated sand by around 187% [31].

Thermal conductivity

The characteristic of a material that specifies how effectively it conducts heat is called thermal conductivity. It represents the amount of heat that can flow through a material per unit time and per unit area, when there is a temperature difference between two points in the material. The unit of thermal conductivity is W/mK (Watts per meter Kelvin) or Btu/(hr•ft•°F) (British Thermal Units per hour-foot-degree Fahrenheit).

Factors affecting thermal conductivity of soil

The ability of soil to transfer heat and its impact on the temperature distribution in soil make soil thermal conductivity an important property for geothermal applications. It influenced not only by the inherent physical properties of each component of the soil but also by the amount of each component present [55]. Soil thermal conductivity is affected by various factors, including the composition of soil (such as mineralogy, grain size, shape, and packing geometry) and environmental conditions (such as saturation level, dry density, and temperature) [37, 56]. soil dry density increases with the amount of precipitated CaCO3 mass [51], The thermal conductivity of soil can be affected by the MICP treatment, which changes the dry density of the soil. In addition, the treatment can increase the contact area between sand particles, which leads to an increase in the thermal conductivity of the sand when it is dry.

Moisture content

Soil moisture content can have a significant impact on thermal conductivity. As soil moisture increases, the thermal conductivity tends to increase [38]. In a study on Jordanian soil, the impact of bulk density, moisture content, dry density, and organic matter on soil thermal conductivity was investigated. The results showed that an increase in moisture content led to a more rapid increase in thermal conductivity for sandy and sandy loam soils, while the increase was less rapid for clay loam and loam soils. This could be attributed to the formation of water films around the relatively larger sand particles, which increased the contact area between them and consequently increased thermal conductivity. However, the effect of moisture content on thermal conductivity depends on several factors such as soil type, porosity, and temperature. Empirical equations or regression models have been developed to model the relationship between soil moisture content and thermal conductivity, taking into account relevant parameters such as soil type and porosity

Soil type and composition

The thermal conductivity of soil is influenced by its type and composition. Soil types vary in their thermal conductivity, with sandy soils typically exhibiting higher thermal conductivity than clay soils. This is attributed to the larger particle size and lower pore space in sandy soils, which facilitate heat transfer more effectively. Conversely, clay soils have smaller particles and more pore space, impeding heat transfer and resulting in lower thermal conductivity [42]. According to the study, the texture of a soil plays a significant role in determining its thermal conductivity at a particular density and moisture content. Coarse-textured soils generally have higher thermal conductivity compared to fine-textured soils. Additionally, the mineral composition of the soil affects its thermal conductivity, with minerals such as quartz giving higher values, while those like plagioclase feldspar and pyroxene, which are found in basic rocks, giving lower values.

Soil density

The density of soil plays an important role in determining its thermal conductivity. Soil with higher density generally exhibits higher thermal conductivity because the particles in denser soil are more tightly packed, allowing for better transfer of heat energy between them. As the bulk density of soil increases, the contact between individual particles becomes more intimate, leading to an increase in thermal conductivity [49]. The thermal conductivity of sandy soil was found to be higher than that of other soils across all bulk densities. It was observed that as the bulk density increased, the thermal conductivity also increased in all soil types due to the improvement of particle contact resulting from a decrease in porosity.

Salt concentration and Organic Matter

Little research has been conducted on the effects of salts on soil thermal conductivity. However, studies have shown that increasing salt concentration in soil solutions can decrease the apparent thermal conductivity of soils. The thermal conductivity of quartz sand, for example, is not significantly affected by CaCl2 or NaCl concentrations up to certain limits, but is lowered when moistened with a solution of KOH. Additionally, soils containing significant amounts of clay can experience reduced thermal conductivity due to the interactions between clay particles and salt ions causing flocculation and aggregation. Furthermore, the presence of organic matter in soil samples has been found to decrease the thermal conductivity of clay loam soil.

Thermal conductivity measurement techniques

Several theoretical and experimental methods for measuring thermal conductivity have been put forth in recent years. Thermal conductivity is an important physical property of materials that characterizes their ability to conduct heat. Accurate measurement of thermal conductivity is critical for understanding the behavior of materials in various applications, such as in thermoelectric devices, thermal management systems, and building insulation. Thermal conductivity tests are either based on measuring the power required to produce a constant temperature difference, applying a constant power and measuring the resulting temperature difference, or monitoring the temperature as it changes [8].

Steady State Methods:

The steady state technique measures the thermal properties of a material once it has achieved complete equilibrium. This means that the temperature at every point in the material remains constant and does not change with time.

Guarded Hot Plate Method:

The guarded hot plate method, which is commonly used to measure the thermal conductivity of large samples of thermal insulation, is not suitable for soils due to the size of the specimens required, despite their low thermal conductivity[9]. A highly precise method for measuring the thermal conductivity in engineering applications is the guarded hot plate apparatus[35]. The guarded hot plate method is a widely used and flexible technique for measuring the thermal conductivity of non-metallic materials including insulation materials, polymers, ceramics, and glass. The method utilizes either a single specimen or a two-specimen apparatus, both of which are capable of operating at temperatures ranging from 80 K to 800 K. The uncertainty associated with the thermal conductivity measurements using this method is approximately 2%. The guarded hot plate method involves a hot plate surrounded by guard heaters and insulation, which ensures that heat only passes through the test specimen. This is considered an accurate and absolute method of measuring thermal conductivity. To obtain accurate results, it is important to establish steady-state conditions and accurately measure relevant parameters such as heat flux, specimen thickness, and temperatures at hot and cold surfaces [11].

Axial Flow Method

The axial flow method has been widely used in literature and is known for providing highly accurate results. It is particularly useful for measuring thermal conductivity at temperatures below 100 K due to minimal heat losses. This method is best suited for small specimens with thermal conductivities greater than 1 W/(m*K) and when simultaneous measurements of other transport properties are required. The main challenge in this method is to minimize radial heat losses in the axial heat flow. To perform the measurement, a sample column is created by sandwiching a test specimen of unknown thermal conductivity between two reference specimens of known thermal conductivity. The sample column is then subjected to a temperature gradient created by a heater at one end and a heat sink at the other end, and the resulting temperature gradient is measured through the test specimen [29].

Heat flow meter method

The basic idea for the heat flow meter method is to determine the heat flux by measuring the temperature difference across a thermal resistor during steady-state conditions. The design of the heat flow meter method is quite similar to the single-specimen guarded hot plate apparatus, with the difference that the main heater is exchanged with a heat flux sensor. Thermal resistors with a number of thermocouples are used as heat flux sensors. In some cases, a heat flux sensor is placed at the cold plate to determine radial losses and reduce the time duration of measurements. The method is mostly used for polymers and insulation materials where the thermal conductivity is less than 0.3 W/(m*K) and an uncertainty of 3% can be accomplished [10]. However, if losses in radial direction are present the uncertainty increases rapidly. The conventional heat flow meter method assumes one-dimensional conduction for heat transfer, i.e. no convection or radiation present. This assumption is reasonable if the test specimen is thin in the direction of heat flow and has a large cross-section area. The surface area for convection and radiation becomes negligible compared to the conductive heat transfer through the specimen and the method is suited for materials with low thermal conductivity. However, for materials with high thermal conductivity, a thicker test specimen is required to be able to measure the temperature difference. This results in doubt of the accuracy of the measurements since convection and radiation will then be present. Convective heat losses can be minimized by performing the experiments under high vacuum conditions. The technique is ideally suited for testing anisotropic specimens and is very accurate and reliable when measuring thermal conductivity on one dimensional heat flow [33].

Advantages and disadvantages of the steady-state methods to other methods are as follows

The steady-state method has numerous advantages over other methods, including its straight forward mathematical expression, ability to provide accurate absolute measurements for low conductivity specimens, reasonable time consumption, and compatibility with different forms of materials. The method can also handle small test specimens, except for concentric spheres, and typically yields uncertainties of 1-2% for insulations near room temperature.

However, the steady-state method has some drawbacks. Achieving high accuracy can be complex, and uncertainties may exceed 10% due to various conditions. The method is also time-consuming and may produce errors due to contact resistance, difficulty measuring geometrically-shaped specimens, and heat losses in some types of setups. Additionally, measuring the heat-flow value for two specimens and moisture-containing specimens can pose challenges [39].

Transient heat flow method

Transient methods are advantageous mainly due to their ability to obtain various thermal values in a short amount of time. This method relies on measuring a signal and maintaining an acceptably small temperature differential. The transient technique involves transmitting a signal to the specimen to generate heat, and then evaluating the feedback response. Test time can be as short as a few minutes or even subsecond intervals, making it a fast method. This technique is especially suitable for materials with high moisture content since the signal and response in the specimen can be reliably measured. In certain cases, it may be possible to replace the need for temperature measurements at two opposite surfaces with a measurement taken as a function of time at only one position on the specimen [16].

Hot-wire method

The hot-wire method is a transitory technique that involves determining the temperature rise at a predetermined distance from the heat source. It is a useful method for determining the thermal conductivity of liquids. In the hot-wire method, the use of a heat source simplifies the specimen preparation, except in the case of solids. For testing solids, the wire is placed between two equally-sized, homogeneous specimens. The hot wire is embedded in small channels, and it is essential to ensure that the contact resistance between the solid specimens and the heating wire is sufficiently low [16]. For measurements on solids, the hot-wire approach is therefore avoided in favour of the hot-strip method, a variation that is growing in popularity.

Hot-disk method

The Gustafsson probe or the hot-disk method, also known as the transient plane source (TPS) technique, is a recent modification of the hot-strip method. It can determine both thermal conductivity and thermal diffusivity. Unlike the steady-state technique, the TPS method eliminates the effect of contact resistance in the analysis, ensuring more accurate measurements. The TPS technique can accurately measure thermal conductivity within a range of 0.005 to 500 W/(m K) at temperatures ranging from 30 to 1200 K [21]. The TPS method is employed to determine the thermal conductivity of both insulating and electrically conductive materials [3]. The primary benefits of using the hot-disk technique are its speedy measurement results, usually obtained in less than 10 minutes, and its ability to accommodate various specimen types by using different sensor sizes. In addition, this method typically employs smaller specimen sizes compared to other techniques [3].

MICP technique

Engineers are familiar with several traditional methods of treating soil for engineering purposes. In the past century, different ground improvement techniques involving the use of chemical solutions or grout have been developed and are commonly applied in geotechnical engineering projects. However, many of these methods can cause contamination to the soil and surrounding environment, and they tend to be costly [20]. MICP, which stands for microbially induced calcite precipitation, is an up-and-coming field of study that has gained greater attention among researchers due to its potential as a sustainable approach to enhancing soil quality [22, 17].

Mechanisms of microbially induced calcite precipitation

MICP aims to enhance soil quality by producing calcite, which is formed as a result of metabolic activities by microorganisms, altering the surrounding water phase. The process can be facilitated by microorganisms attaching to the porous subsurface environment and engaging in collective metabolic activities such as urea hydrolysis, photosynthesis, sulfate reduction, denitrification (nitrate reduction), ammonification, or methane oxidation. These activities increase the saturation of calcium carbonate, leading to the formation of calcite, which ultimately improves the soil properties [12, 52]. According to research reported by Zhu and Dittrich60, urea hydrolysis is the most advanced method currently in use among the several processes mentioned above that lead to the formation of calcite. According to Mujah36, ureolysis is chosen by researchers over photosynthesis because it is simple to precipitate calcite ($CaCO3$) and can accomplish up to 90% chemical conversion efficiency of calcite in less than 24 hours. Sulphate reduction is another MICP process that has been extensively explored, according to Zhu and Dittrich60, though its engineering advantage is typically given less emphasis.

Factors that affect the microbially induced calcite precipitation technique

Although not always optimal, biocalcification activity in soils can vary significantly based on physiochemical characteristics including temperature, the microenvironment's nutrient content, and the type, source, and activities of the organisms.33. Several studies have shown that there are mainly following factors that affect the microbially induced calcite precipitation techniques; concentration of cementation reagents, geometric compatibility, pH, temperature, bacterial suspension density.

Application of MICP technique

The technique of Microbially Induced Calcium Carbonate Precipitation (MICP) is widely applicable in geotechnical engineering, and there are several examples of its usage. One such example is using MICP to strengthen weak or unstable soils by introducing bacteria that produce calcium carbonate, resulting in increased soil strength and stiffness. Additionally, it can prevent soil erosion by binding soil particles together with calcium carbonate, and improve soil properties such as density and drainage by adding nutrients and microorganisms. It can also improve the bearing capacity of soil for foundation support and reinforce soil for slope stabilization and retaining wall construction. However, further research is needed to better understand the long-term performance and durability of MICP-treated soils.

Thermal conductivity and MICP

Ground heat exchangers that use energy piles make use of the soil's high thermal storage capacity and are considered to be a reliable, cost-effective, and environmentally friendly technology that is rapidly gaining popularity worldwide. Although the bio-cementation of soils has mostly been studied in laboratory settings, there is evidence to support its feasibility on a larger scale for cementing larger volumes of soil. This technique's main advantage is the low viscosity of the treatment solutions used, which allows for the circulation of reactants in targeted areas without eroding the in-situ soil. Studies, both numerical and experimental [14], have demonstrated that the exchange of heat in dry conditions may be up to 40% less efficient than in fully saturated conditions. To address this issue, the use of Microbially Induced Calcium Carbonate Precipitation (MICP) is proposed. By inducing MICP, the structure of the soil can be altered, resulting in the formation of intergranular calcite bridges that increase the overall thermal connectivity of the solid matrix. This, in turn, enhances the soil's thermal conductivity, which is the measure of the ability of the multicomponent medium (comprising air, water, and solid) to conduct heat. The soil's apparent conductivity is influenced by various structural factors, including water content, mineral composition, bulk density, porosity, and temperature [5]. All of the aforementioned elements are impacted by MICP, but porosity, soil mineral constitution, and average soil dry density are most affected. The latter increases with the amount of precipitated calcium carbonate mass [51] and this increase is considered to reflect on the thermal conductivity of the treated soil, provided λ increases linearly with dry density [49]. Experimental observations [40, 15, 46] suggest that the rate of change of thermal conductivity, with respect to saturation S, varies depending on the saturation regime. Three different saturation regimes have been identified based on the relationship between soil saturation (S) and soil thermal conductivity (λ). The first regime is called the pendular regime, which occurs when S is less than or equal to 0.2. This regime is characterized by significant variations in λ as S changes. The second regime is called the funicular regime, which occurs when S is between 0.2 and 0.9. In this regime, λ changes are mild. The third regime is called the capillary regime, which occurs when S is greater than or equal to 0.9. In this regime, there are no significant changes in λ [46]. The thermal conductivity of bio-treated sand can increase the thermal conductivity upto 250% when compared to the untreated sand. The MICP treatment is used to enhance the heat transfer efficiency in sand at lower degree of saturation.

CONCLUSION

Based on the review of literature, it can be inferred that the thermal conductivity of soil is important in geotechnical engineering, and is influenced by factors such as density, moisture content, and microbes. The thermal conductivity can be determined through various field and laboratory methods. The most accurate laboratory method is the Guarded Hot Plate, but it is time-consuming. The Thermal Probe method is a faster alternative that provides satisfactory results. Microbes, such as *Sporosarcina pesturii*, can affect the thermal conductivity of soil by aggregating soil particles. However, the commonly used method for this, known as the Microbial-Induced Calcite Precipitation (MICP) technique, requires a cementation solution that can have negative environmental impacts. Therefore, it is important to develop sustainable, cost-effective, and eco-friendly methods to alter the thermal conductivity of soil.

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