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A Critical Review on Enhancing Thermal Conductivity of Sandy Soils Using Nano Aluminum Oxide (Al_2O_3) under Different Moisture Conditions

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ABSTRACT: This review synthesizes up-to-date research on enhancing thermal conductivity in natural sandy soils, a key parameter for improving the utility of Ground Source Heat Pump (GSHP) systems and many geotechnical applications. The review is structured around four key research areas that capture the interdisciplinary context of this research. These areas of study include: the studies, which incorporate mineral and non-mineral synthetic additives into sandy soils to improve thermal connectivity and density with particle contact during loading; the other research area included moisture, which was found to improve thermal connectivity with particle contact, and therefore thermal transfer, when all air voids were filled; there were also studies that investigated the effects of nanomaterials, with a strong emphasis on nano aluminum oxide (Al_2O_3), that focused on mechanical properties for sandy soils, such as; strength, and cohesion. Al_2O_3 improved these properties of sandy soils which were factors indirectly assisting enhanced thermal pathways; and lastly, there are other studies that looked at the applications of Al_2O_3 as a heat transfer medium in nanofluids, and phase change materials (PCMs), which provide consistent improvements in thermal performance and superior thermal management. The challenge is that, while areas of investigation have been explored, substantial gaps remain in our understanding of how nano-Al_2O_3 and moisture variability interact to affect the thermal conductivity of sandy soils, particularly in tropical weather and conditions. This study discusses the gap identified above, addresses its applicability, and identifies potential experiments for future work.

KEYWORDS: Nano Aluminum Oxide (Al_2O_3), Sandy Soil, Moisture Content, Thermal Conductivity, and Ground Source Heat Pumps (GSHP).

1. INTRODUCTION

As sustainability drives both more construction and programs to improve sustainability globally, reducing energy and carbon across all aspects of development has become even more significant. HVAC (heating, ventilation, and air conditioning) contributes significantly to energy usage in buildings. Consumption in developing countries is estimated to account for roughly 35% of global electricity use, mostly from fossil fuels, which also increases greenhouse gas emissions and contributes to climate change (World Bank Group, 2017). Energy-efficient technologies have gained traction as GSHP, or ground source heat pump, systems are increasingly used as one of the most sustainable HVAC options for heating and cooling buildings. GSHP systems take advantage of the relatively constant temperatures below the ground surface and perform thermal energy transfer. Compared to conventional HVAC systems, GSHP systems operate at higher thermodynamic efficiency. In Europe and North America, the broad acceptance and use of GSHP is undoubtedly justified as a long-term, cost-effective solution with sustainable support (Ma et al., 2020).

The properties of the surrounding soil play a major role in the performance of any GSHP system, particularly thermal conductivity (k), which controls the heat transfer from the ground to the heat exchanger (Ma et al., 2020). This variable is dependent on many soil properties, including moisture content, dry density, particle-size distribution, and the mineralogical makeup of the soil (Toan et al., 2021). Of these properties, moisture plays a key role because water, as a solid or liquid, conducts heat better than air. Moisture increases particle-to-particle contact (Kokoreva et al., 2024). Higher dry density reduces air voids and improves heat transfer. Particle size and mineralogy both affect thermal behavior, especially quartz (Toan et al., 2021). While these factors are important, predicting thermal conductivity is difficult when soil is heterogeneous, and site conditions vary by location. Conventional sandy soils common in most tropical climates often have low thermal conductivity, typically below 1 (W/m·K); low conductivity is often increased by hydrological properties, permeability, and moisture retention (Alrtimi et al., 2016; Kokoreva et al., 2024).

To mitigate low conductivity in sandy soils, researchers have introduced additives to enhance heat transfer. Nanotechnology has received the most attention as an additive in innovative geology research. Nano aluminum oxide (Al_2O_3) or nano-alumina has seen extensive studies and exhibits a potential for being an additive to sandy soils based on its high intrinsic thermal conductivity estimated at 46 W/m·K, chemical and thermal stability, environmental sustainability, and cost-effectiveness (Ezzat & Hasan, 2014; Pereira et al., 2023; Tiwari & Feng, 2024). Previous applications of nano-additive materials have primarily focused on improving geomechanical properties such as overall strength and cohesion (Kermanipour, 2024; Niroumand et al., 2023). Little is known about its thermal properties, where moisture continuously alters a soil's thermal behavior; therefore, a significant and pertinent knowledge gap remains. As supporting rationale, the area of nanotechnology has recently grown within energy research, including nanofluids, PCMs and composites where researchers consistently confirmed that they have improved heat storage and diffusion (Huang et al., 2024; Samara et al., 2024; Vickram et al., 2024), which provides a qualified ground for using Al_2O_3 in sandy soils (or soils with porosity) too.

The purpose of this review is to: (1) outline some recent research examining moisture-dependent conductivity in sandy soils, (2) review enhancement efforts using various soil additives to improve thermal properties, (3) outline the knowledge gaps with nano-Al_2O_3 based on moisture, (4) transfer existing information from evidence gained from the study of PCMs and nanofluids to soil systems, and (5) provide recommendations on where to go next in subsequent research to improve or benchmark GSHP systems especially as a new approach for research in Malaysia and other tropical areas. The novelty of this review lies in integrating four areas of evidence that have generally been examined separately: moisture-dependent thermal behaviour of sandy soils, thermal enhancement using mineral and non-mineral additives, mechanical and microstructural effects of

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nano-Al_2O_3 in soil-based systems, and the thermal behaviour of nano-Al_2O_3 in non-soil media. By comparing these areas together, the review identifies the unresolved question of whether nano-Al_2O_3 can modify the moisture-dependent thermal response of sandy soil. This integrated perspective provides a focused basis for future controlled studies under tropical moisture conditions, while avoiding the direct transfer of findings from nanofluids, phase-change materials, or mechanically stabilised soils to sandy-soil thermal performance.

2. REVIEW METHODOLOGY

A structured critical review was conducted to identify and evaluate published evidence relevant to the thermal conductivity of sandy soils, moisture-dependent thermal behaviour, soil thermal enhancement using mineral and non-mineral additives, and the mechanical or thermal effects of nano aluminum oxide (nano-Al_2O_3) and related nanomaterials. Relevant literature was identified using Scopus, Web of Science Core Collection, Google Scholar, and reference-list screening. The primary search covered June 2015 to May 2025, while earlier key studies and recognised technical standards were retained where necessary to support fundamental concepts or measurement procedures. Search terms included combinations of "nano-Al_2O_3", "nano alumina", "aluminum oxide nanoparticles", "sandy soil", "sand", "thermal conductivity", "thermal resistivity", "moisture content", "soil stabilization", and "heat transfer". Priority was given to peer-reviewed studies that clearly reported the investigated materials, soil type, treatment conditions, additive dosage, moisture or saturation condition, measurement method, and quantitative thermal, mechanical, or microstructural findings.

The parameter ranges discussed in this review were not independently selected by the authors but were extracted from the experimental or numerical conditions reported in the original studies. Particular attention was given to additive concentration, moisture content, soil type, density, temperature, and thermal-measurement procedure because these factors can influence the reported thermal response. Direct numerical comparison between studies was therefore made cautiously when experimental conditions were not equivalent. Where available, repeated measurements, reported experimental variability, model sensitivity, goodness-of-fit, and methodological limitations were considered when assessing the reliability of the reported findings. Studies involving nano-Al_2O_3 in nanofluids and phase-change materials were used only as supporting mechanistic thermal evidence and were not treated as direct evidence of thermal enhancement in sandy soil.

3. LITERATURE REVIEW

3.1 Introduction

Soil thermal conductivity is an important property affecting technologies such as ground source heat pumps (GSHPs) and thermal backfill systems (Ma et al., 2020). Sandy soils generally have lower thermal conductivity than finer-grained soils, creating a need for thermal enhancement (Kokoreva et al., 2024). Soil thermal conductivity depends mainly on mineral composition, moisture content, dry density, pore structure, and additives that modify thermal pathways (Panugothu & Kadali, 2024; Wu et al., 2025).

Nano-Al_2O_3 has attracted interest in geotechnical engineering because of its thermal properties, chemical inertness, and nanoscale interactions (Ezzat & Hasan, 2014; Sun et al., 2025). Its addition may improve thermal pathways between soil particles, while moisture may enhance thermal contact between grains. This review therefore examines the combined influence of moisture and nano-Al_2O_3 on the thermal conductivity of sandy soils through four themes: (1) Soil additives and thermal improvement, (2) Moisture effects on thermal behaviour, (3) Nano-Al_2O_3 for mechanical enhancement, and (4) Thermal performance in nanofluid systems. These frameworks highlight the need for integrated research on the combined effects of moisture and nano-Al_2O_3 on soil thermal properties.

3.2 Thermal conductivity of soil

Soil thermal conductivity is the ability of the soil to conduct heat through a thermal gradient based on Fourier's Law (Farouki, 1986). Thermal conductivity measures how effectively heat is transferred across the soil matrix of solids, water, and air (Panugothu & Kadali, 2024), and is essential for designing systems such as ground heat exchangers, buried cables, and thermal barriers. Moisture is the primary governing factor, as water has a significantly higher thermal conductivity (~0.6 W/m·K) than air (~0.025 W/m·K) (Rizvi et al., 2022; Wu et al., 2025). Water occupies the soil pores, increasing thermal contact and reducing thermal resistance. In sandy soils, higher moisture improves conductivity by providing a more continuous heat-flow pathway (Panugothu & Kadali, 2024; Wu et al., 2025).

Mineralogical composition is also important. Soils with high quartz content, like clean sands, and moisture can reach thermal conductivities greater than 2.0 W/m·K, while clays and silts are typically lower due to their greater porosity (Rizvi et al., 2022; Wu et al., 2025). Bulk density and compaction improve thermal conductivity through reduced air voids (Panugothu & Kadali, 2024). Freezing changes soil thermal conductivity while creating phase changes and thermal interfaces in cold climates. Conductivity at freezing may improve, but impurities such as hydrocarbons can disrupt ice conductivity (Wu et al., 2025).

3.3 Overview of Nano Aluminum Oxide (Al_2O_3)

Nano aluminum oxide (Al_2O_3), also known as nano alumina, is a widely studied nanomaterial with impressive thermal, mechanical, and chemical properties. Nano alumina generally appears to be a white to tintless, undetectable powder, is water insoluble, and exists in various crystalline forms - α, δ, and γ - which have different properties (Congreve et al., 2024). The α-Al_2O_3 phase has heat resistance and high density, giving it potential for very high-temperature applications. Depending on the fabrication method (e.g., sol-gel), particle sizes range from approximately 30 nm to several hundred nm. It has a high surface area and can encourage interaction with host materials (Zou et al., 2024).

Some of the alumina surface properties that allow its application versatility include thermal resistance, biocompatibility, electrical resistance, hardness up to 19.9 GPa, and Applications for nano alumina include ceramics, coatings, catalysts, and biomedical apparatus (Al-Hussain et al., 2022; Congreve et al., 2024; Y. Li et al., 2023). Nano alumina has a thermal conductivity of approximately 46 W/m·K and a melting point of approximately 2200 K. These properties differ from those of commercially marketed metal oxides, which can also be used in thermally conductive composites and nanofluids (Ezzat & Hasan, 2014; Tiwari & Feng, 2024). Nano alumina is designed to be stable at high temperatures, which can facilitate long-term performance (Sun et al., 2025).

Nano alumina can be fabricated by sol-gel processing, hydrothermal processing, and via recycling aluminum waste, a low-cost and environmentally friendly method (Alabada et al., 2023; Mokaizh & Shariffuddin, 2021). Nano alumina may benefit thermally enhanced geotechnical systems with varying moisture content.

3.4 Measurement of soil thermal conductivity

Thermal conductivity is an important consideration for geotechnical and energy applications, specific to Ground Source Heat Pumps (GSHPs), underground heat storage, and subsurface energy systems. The KD2 Pro is a mainstream instrument that utilizes Transient Line Heat Source (TLHS) technology using a needle probe containing very fine heating wire along with a temperature sensor, then uses the rise in temperature to derive thermal conductivity after applying a controlled heat pulse (Adjima et al., 2023; Deshmukh et al., 2022). Figure 1 shows the device used for measuring thermal conductivity.
The KD2 Pro is manufactured in accordance with the American Society for Testing and Materials ASTM D5334-08 and the Institute of Electrical and Electronics Engineers IEEE 442-2017 standards and the manufacturers of the KD2 Pro suggest that the TLHS method has

accurate and consistent results suitable for both laboratory and field measurements (ASTM, 2008; IEEE, 2017). The KD2 Pro has a very fast output time (5–15 minutes); it has demonstrated durability and precision in moist and variable soils and provides quick, instantaneous estimates of thermal conductivity for geotechnical engineering and research applications (Adjima et al., 2023).

Figure 1 KD2 Pro Thermal Properties Analyzer (Source: Geological Survey of Slovenia [GeoZS], 2025).

3.5 Review of previous studies

Recent reports indicate the widespread use of nano aluminum oxide (Al_2O_3) to improve thermal conductivity in various materials. Al_2O_3 nanoparticles can enhance heat transfer in nanofluids, composites, and stabilized soils because their large surface area and high intrinsic thermal conductivity promote thermal bridging and energy transfer. Moisture content is a critical factor affecting the thermal conductivity of sandy soils. Water fills pore spaces, improves particle contact, reduces thermal resistance, and enhances heat conduction. This is particularly relevant in tropical climates, where precipitation and humidity cause considerable variations in soil moisture.

Studies on water-based nanofluids and paraffin-based phase change materials (PCMs) also show improved thermal performance with Al_2O_3. However, nanomaterial modification, moisture effects, and the thermal role of Al_2O_3 are generally studied separately, leaving their combined effects on sandy soils insufficiently understood. This review integrates evidence from these areas to support a coordinated approach for thermally enhanced soils in geotechnical and energy applications, including GSHP systems and thermal backfills.

3.5.1 Studies on mineral additives and moisture influence

Experimental and microstructural studies have examined the thermal conductivity of sandy soils containing mineral and non-mineral additives. S. Li et al. (2023) conducted a laboratory study using bio-cemented quartz sand reinforced with steel slag. Thermal conductivity increased by up to 367%, reaching a maximum of 1.28 W/m·K. However, when the steel slag content exceeded 20%, thermal conductivity decreased because the microstructure became less favorable for efficient heat flow. This indicates that an optimum additive content is needed to maintain structural integrity while improving heat transfer.

In another controlled experiment, Sah and Kumar (2025) investigated bentonite–sand mixtures with varying fly ash contents. Samples containing 50% to 70% fly ash showed favorable thermal performance, indicating that fly ash can support heat transfer in thermal backfill applications. Cheng et al. (2021) provided a more detailed experimental and microstructural investigation by introducing glass, steel, and polyethylene fibres into bio-cemented sand treated with calcium chloride ($CaCl_2$) or magnesium chloride ($MgCl_2$) solutions. Among the investigated fibres, glass fibre showed the highest thermal conductivity.

This improvement was attributed to the formation of continuous thermal bridges within the soil. Steel fibres showed lower long-term effectiveness, which was associated with corrosion and surface degradation, while polyethylene fibres provided the least improvement. Scanning Electron Microscopy (SEM) revealed microstructural changes that supported improved thermal conduction. The SEM images in Figure 2 show calcite crystal precipitation between sand particles after treatment with 100% $CaCl_2$ and $MgCl_2$. These findings indicate that mineral bridges may improve particle connectivity and produce a soil matrix more favorable for thermal conduction.

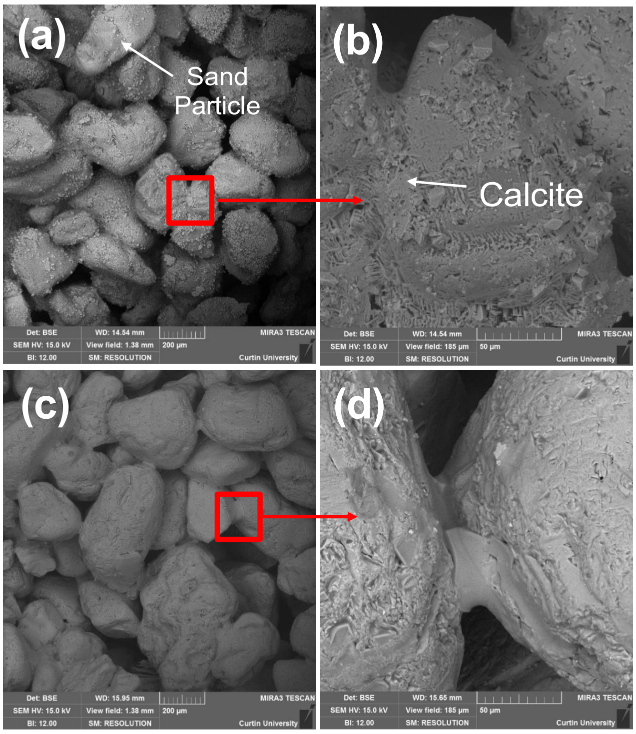

Figure 2 SEM imaging showing microstructure of the soil sample treated with 100% $CaCl_2$ (a,b) and 100% $MgCl_2$ (c,d) (Adapted from Cheng et al., 2021).

Figure 2 shows a comparative experimental setup used to further assess the effects of fibre type and dosage on thermal conductivity, while Figure 3 shows the treatment cycles for three rounds of treatment using cement-based material and the Microbially Induced Calcite Precipitation (MICP) procedure. The treatment cycles were: (a) first treatment, (b) second treatment, (c) third treatment - the dosage levels for each round were 0.5% and 1.0% - the fibre types were polyethylene, steel, and glass.

For each treatment, 1.0% glass fibres consistently provided the highest thermal conduction readings. This suggests glass fibres provide more retention of their thermal bridging properties after multiple uses. In treatment one, steel fibres contributed to thermal conductivity values, and thus, based on treatment one, steel fibres worked very well. However, in treatment three, the steel fibre effect drops significantly, suggesting the steel fibre may have undergone some dissolution and degraded its bonding to the matrix over time. In contrast, polyethylene fibres enhanced thermal conductivity values in comparison to the un-fibred composite in each of the treatments, but only marginally; we suspect that this is attributable to the low thermal conductance of polyethylene fibres and the relatively low binding ability to a cementitious matrix.

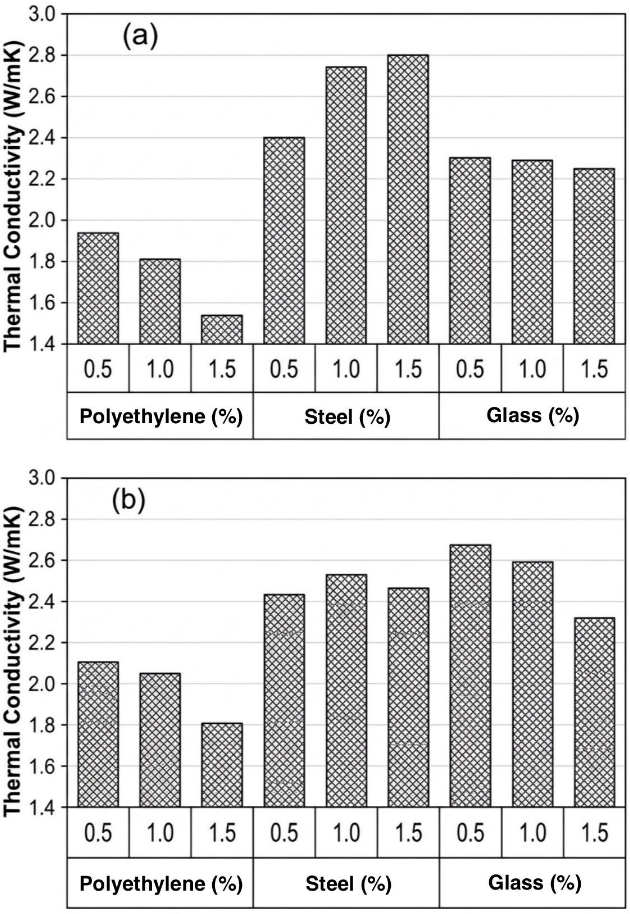

Figure 3 Thermal conductivity of fibre–sand mixture after MICP treatment: (a) 1st treatment; (b) 2nd treatment; and (c) 3rd treatment (Adapted from Cheng et al., 2021).

Overall, these studies support that moisture control and mineral modification can improve the thermal performance of soils. However, most of the available literature, although extensive, is mainly limited to macro- and micro-size additives, while the use of nanomaterials under varying moisture conditions remains less investigated. This creates a clear need to examine how nanoscale additives may interact with changes in soil moisture and influence heat-transfer mechanisms. This review therefore proposes nano aluminum oxide (Al_2O_3) as a potential mineral additive that can leverage its nanoscale characteristics to improve inter-particle contact, reduce thermal resistance, and promote thermal bridging within sandy soils. These effects may become particularly important as moisture content changes, because water can alter particle contact and the continuity of heat-transfer pathways. Such an integrated approach may support the development of high-performance thermally conductive backfill materials for geotechnical and energy applications, especially in hot and humid environments such as Malaysia, where soil moisture can vary considerably under field conditions.

3.5.2 Influence of moisture content on soil thermal behavior

Moisture content is widely considered a main factor controlling the thermal response of sandy soils. Substantial experimental and statistical evidence shows that increasing moisture content generally increases soil thermal conductivity. This occurs mainly because water replaces air within the soil pores, improves thermal contact between adjacent soil grains, and creates more continuous pathways for heat conduction. Because water has a considerably higher thermal conductivity than air, replacing air-filled voids with water-filled spaces reduces the overall thermal resistance of the soil matrix. However, the magnitude of this improvement may vary depending on soil texture, density, pore structure, and the range of moisture content investigated. Experimental and modeling work by Kokoreva et al. (2024) also showed that moisture content increased the thermal conductivity of synthetic and urban soils. Enhanced particle connectivity and reduced thermal resistance within the pore space were identified as important mechanisms responsible for this behaviour. Their study also examined the applicability of existing empirical prediction models under different moisture conditions. The results indicated that thermal conductivity models can provide useful estimates, although their performance may vary depending on soil characteristics and moisture range. This is important when comparing results between studies because similar moisture contents may not produce identical thermal responses when soil composition, density, and testing conditions differ.

In a similar controlled laboratory study, Kaveh et al. (2021) examined the interaction between soil moisture content, soil texture, and different salinity levels using three soil types: sand, sandy loam, and silt loam. Their results further confirmed moisture content as a major factor controlling soil thermal conductivity. The study presented a non-linear relationship between changes in moisture content and thermal conductivity across soil textures using second-degree polynomial regression models. Salinity was also considered because dissolved salts can modify the thermal behaviour of the pore water and its interaction with soil particles, although the response varied among the investigated soil types. Figure 4 presents these relationships, showing how thermal conductivity varies with moisture content, salinity, and soil type. The violin plots in Figure 4A illustrate the distribution and variation of conductivity values under the different conditions, whereas the line plot in Figure 4B shows an overall increasing trend in thermal conductivity with increasing moisture content. Sand and sandy loam showed particularly noticeable responses to moisture variation. Overall, these studies demonstrate that moisture improves heat-transfer pathways in sandy soils, but the resulting thermal conductivity depends on the combined effects of soil texture, pore conditions, density, and other environmental factors such as salinity. This interaction is particularly relevant when evaluating thermally enhanced sandy soils under variable moisture conditions.

Similarly, Dai et al. (2022) conducted depth-profile studies to measure thermal diffusivity across varying moisture content conditions, and their results indicated that moisture and density affected thermal behavior across soil layers, particularly at representative depths under field conditions. They also presented predictive models that considered moisture variability and thermal performance to better estimate diffusivity under specific environmental conditions. Although studies similar to Dai et al. (2022) exist, much of the literature still relies on traditional soil–water relationships when examining the collective influence of advanced additives. This review highlights a comprehensive consideration of moisture and nanoscale engineered materials in assessing thermal response, expanding on limited research on advanced soil materials, particularly nano aluminum oxide (Al_2O_3). Because of its high surface area and strong thermal conductivity, Al_2O_3 may work with moisture to create continuous thermic micro-channels. This integrated assessment opens new opportunities to realize thermally efficient, energy-responsive soils—most relevant to hot, humid climates constrained by soil moisture variability and the need to regulate thermal conditions for underground energy infrastructure.

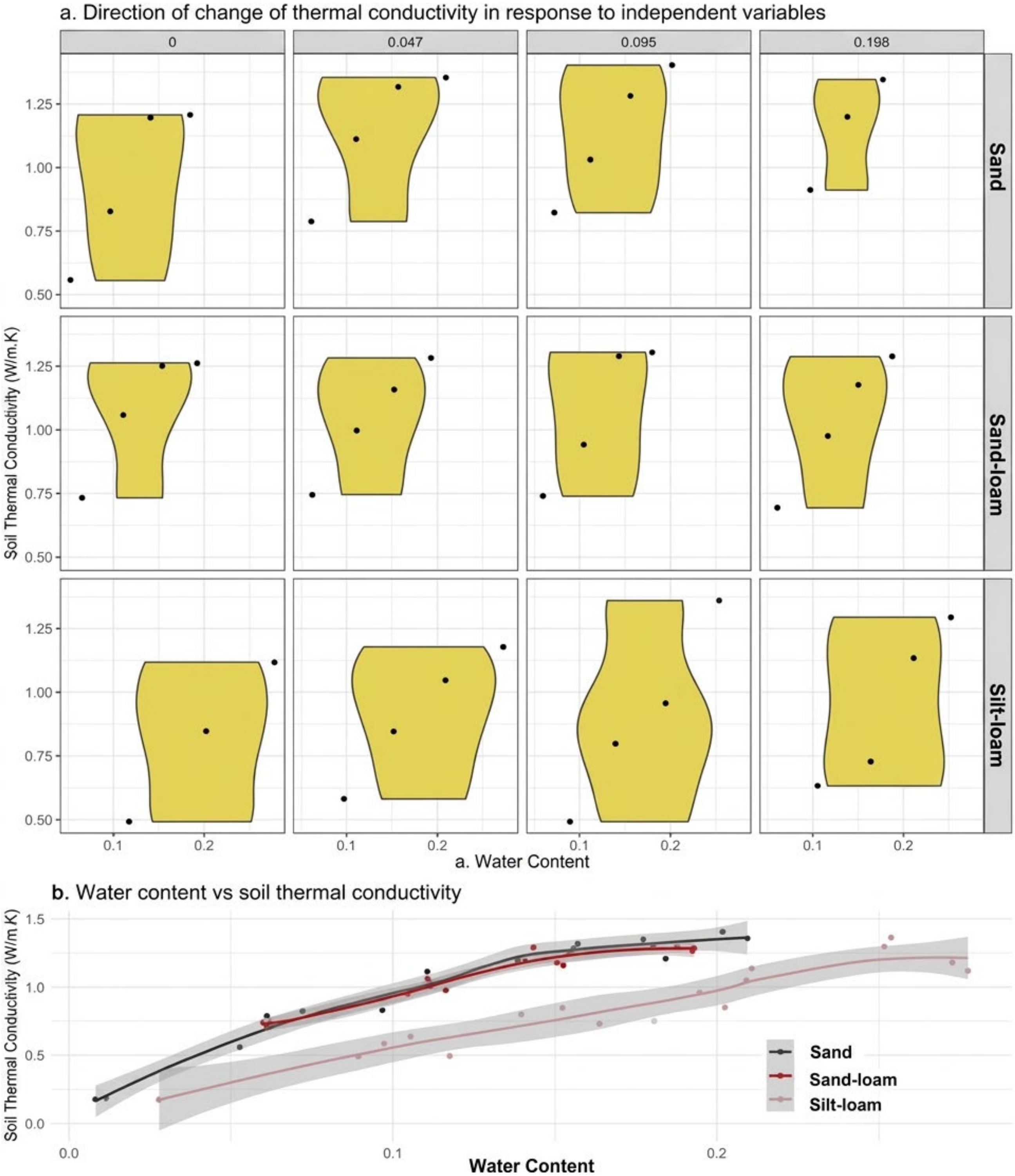

Figure 4 Direction of change in thermal conductivity in response to soil type, salinity (Mol NaCl/Kg), and water content (m^3/m^3) (Adapted from Kaveh et al., 2021).

3.5.3 Nano-Al_2O_3 for mechanical enhancement of sandy soils

Advancements related to soil stabilization have shown that nanomaterials can improve the mechanical properties of sandy soils, particularly through the use of Nano Aluminum Oxide. Both experimental and review-oriented research has shown that nano-Al_2O_3 improves micro-bonding between soil particles, which can enhance soil strength, stiffness, and cohesion. Kermanipour (2024) conducted a research project exploring the mechanical properties of sandy soils blended with industrial waste products and nanomaterials. The study examined varying amounts of non-metallic nanomaterials, which were admixed with the parent precursors Ground Granulated Blast Furnace Slag (GGBS) and Recycled Glass Powder (RGP). The source materials were mixed with alkaline activators represented as PAS (Poly Aluminum Silicate) and PCS (Poly Calcium Silicate).

Nanoscale materials can modify contact conditions between soil particles and may contribute to a denser, more connected soil structure. Such changes are important because improved bonding and reduced void spaces can influence the overall behaviour of stabilized sandy soils. The interaction between nanoparticles, industrial waste materials, and soil particles may therefore provide a stronger internal structure compared with untreated materials. In addition, nanoscale particles may occupy smaller spaces between larger soil or binder particles, improving packing and increasing contact between components of the treated soil matrix. These mechanical and microstructural changes are also relevant to the present review because particle contact, pore structure, and internal connectivity are among the factors that can influence heat-transfer pathways within soil systems. Therefore, although these studies mainly focus on mechanical behaviour, they provide useful supporting information when considering how nanoscale modification may affect the internal structure of sandy soils.

Incorporating nano-related materials significantly enhanced the mechanical performance of the treated soil mixtures. Figure 5 illustrates the mechanical improvements achieved. The upper graph presents the RGP-based samples, while the lower graph presents the GGBS-based samples. Both show changes in Unconfined Compressive Strength (UCS) with increasing nanomaterial content. GGBS–PAS samples achieved UCS values approaching 3000 kPa at 2.0% content, while the PCS-based samples showed more modest changes. The stronger response of the GGBS–PAS system indicates that the effect of nanomaterial addition may also depend on the precursor type and the interaction between the stabilizing components. This suggests that nanomaterial dosage alone may not determine the final mechanical response, as the composition of the treated soil system can also play an important role.

These findings demonstrate the potential of nanoscale additives to improve the mechanical behaviour of geopolymer-based soil systems. However, the reported improvements were mainly based on mechanical properties such as UCS and should not be considered direct evidence of improved thermal conductivity. Instead, they provide supporting evidence that nanoscale modification can alter soil bonding, particle contact, and microstructure, which may be relevant when investigating the thermal behaviour of nano-modified sandy soils under different moisture conditions. Further thermal studies are therefore needed to determine whether these structural improvements can also produce measurable changes in heat-transfer performance.

The mechanical enhancement associated with nano-related treatment was clear; however, these studies mainly focused on strength and stiffness rather than thermal behaviour. There has been limited focus on the thermal behaviour of nano-modified sandy soils. Therefore, this review aims to redirect attention to the thermal performance of sandy soils doped with nano-Al_2O_3 at different moisture contents. If both mechanical and thermal properties improve, nano-Al_2O_3 may be a viable multifunctional additive that provides structural support and thermal enhancement for a broad range of applications, including geothermal systems, underground cable backfill, and hot and humid-region environments.

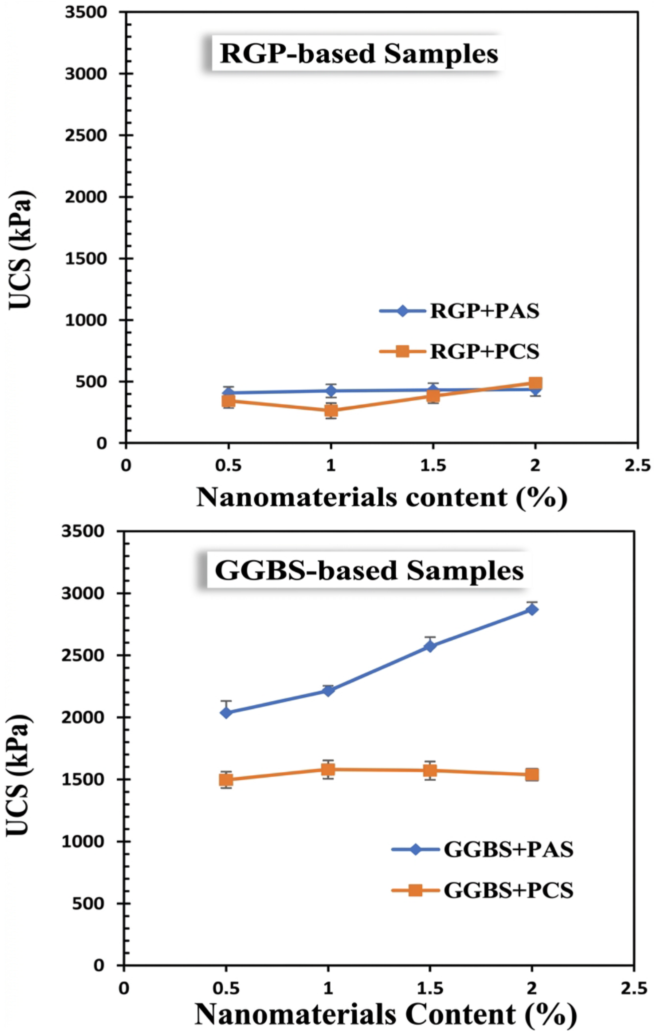

Figure 5 UCS of RGP- and GGBS-based samples with varying nanomaterial contents (Adapted from Kermanipour et al., 2024).

3.5.4 Thermal enhancement using Nano-Al_2O_3 in fluids

While prior sections discussed solid-phase materials such as sands and geopolymers modified soils, the thermal behavior of nano-Al_2O_3 must also be evaluated in nanofluids and PCMs. Although these phases differ from soils, the principles of thermal enhancement with Al_2O_3 nanoparticles are similar and can provide useful information for geotechnical applications. (Huang et al., 2024) performed a recent computational sensitivity research study on Al_2O_3−H_2O nanofluids, where they studied the effects of nanoparticle shape, temperature, and volume fraction on thermal conductivity. The transition in thermal conductivity depended most on volume fraction, and conductivity increased significantly with nano-Al_2O_3 volume fraction. These findings also highlight the importance of particle loading and spatial dispersion, which may apply to water-filled soil pores, where nano-Al_2O_3 may clump at contact points to enhance conduction.

Experimental work completed by (Vickram et al., 2024) affirmed that this additive effect of Al_2O_3 in a 60 °C ethylene glycol−water mixture with 0.5% nano-Al_2O_3 was discovered to improve thermal conductivity by 27%. This is due to the high surface area and inherent conductivity of the nanoparticles, imparting better thermal transport and thermal conductivity in fluid media. Therefore, the thermal behavior and additive effects of nano-Al_2O_3 in fluid media suggest it is well suited to aqueous or saturated soil environments. Studies conducted by Samara et al. (2024) evaluated paraffin wax-based PCMs with Al_2O_3 nanoparticles as a possible thermal agent, suggesting superior thermal and electrical performance on initial heating, improved thermal storage, and complete stability over multiple cycles. These findings support the notion that nano-Al_2O_3 can provide added benefits over long-term thermal exposure and may also apply to future energy systems such as ground-source heat pumps (GSHPs) and seasonal heat storage in geotechnical applications. Although the nanofluids and PCMs differ in terms of composition, the understanding of mandates in thermal enhancement such as improved particle-to-particle contact, interfacial heat transfer, and thermal bridging should be transferable in behavior and thermal capacity to moist, porous soils. This review expands on the above parameters and conclusions in the context of natural sandy soils with variable moisture, by assessing whether the apparent advantages of nano-Al_2O_3 would directly improve thermal conduction in porous media. Its objective is to assess whether or not nano-Al_2O_3 could be used as a multifunctional thermal additive in geotechnical and energy applications in warm, humid climates.

3.5.5 Overall evaluation of previous studies

The literature showed growing interest in nano aluminum oxide (Al_2O_3) as a multipurpose application for improving thermal and mechanical properties. Al_2O_3 has been shown to improve thermal conductivity for materials such as nanofluids and phase change materials (PCMs) and has been used in engineered soils. The nanoscale material characteristics, including higher potential thermal conductivity and structural stability, create strong potential for using nano-Al_2O_3 to enhance heat transfer through distributed matrices. Some studies also focus on improving sand cohesion mechanically. When mixed into reactive ultra-high-performance concrete (UHPFRC), it affects various properties, including compressive strength/stiffness, inter-microstructural bonds, etc.

Two main variables have been shown to be consistent: the presence of nanomaterial, particularly Al_2O_3, and moisture or water in soils. The thermal conductivity of each has been studied extensively in the literature. Nanomaterials promote inter-particle conduction, and the moisture fills in voids, leading to increases in the amount of contact between each particle. The literature reviewed in this study did not identify direct experimental studies examining the combined effect of varying moisture content and nano-Al_2O_3 on the thermal conductivity of natural sandy soils.

This gap, in two resource forms, was researched as geotechnical applications of thermally efficient materials continue to increase. There may be some non-linear or synergistic effects of the individual variables listed above. This paper aims to fill that gap and report the influence of nano-Al_2O_3 and moisture on the thermal performance of sandy soils, with an emphasis on energy systems, in hot and humid climates.

4. CONCLUSION

This review assessed the many experimental and analytical studies that have addressed the impact of moisture content, Nano Aluminum Oxide (Al_2O_3), and other additives on the thermal and mechanical characteristics of sandy soils and related materials. The literature shows that increasing soil moisture content significantly improves thermal conductivity due to improved interaction between soil particles and reduced void area, especially in sandy soils. In conjunction with increased soil moisture, nano-Al_2O_3 has been shown to be an effective thermal additive in nanofluids, phase change materials, and engineered soil systems due to high thermal conductivity, stability, and surface properties. Nano-Al_2O_3 also has been shown to improve mechanical properties such as unconfined compressive strength and stiffness, particularly in cementitious or geopolymer-treated soils. Therefore, it serves as a multifunctional soil additive.

Nonetheless, a key gap remains: the effects of nano-Al_2O_3 alone, or in conjunction with changing moisture content, on the thermal conductivity of natural sandy soils have not been sufficiently evaluated. Most current research has evaluated these conditions separately, and few studies provide perspective based on thorough evaluations of real field conditions or tropical soil, warranting future experimental research on synergistic effects. Closing this gap could enable the development of thermally enhanced, environmentally friendly treatment of sandy soil, increasing energy efficiency in GSHP systems and other geotechnical applications in humid tropical regions facing rising energy demand.

5. RECOMMENDATIONS

Based on a comprehensive review of the literature and prior research conducted for this study, this study provides the following recommendations:

1. Conduct future experimental investigations of the effects of nano aluminum oxide (Al_2O_3) on the thermal conductivity of natural sandy soils under varying moisture conditions.
2. Investigate the effects of time on the nano-treated soils with respect to wetting-drying cycles and temperature, to evaluate the permanence of the thermal properties.
3. Develop predictive models of soil properties, moisture and nano aluminum oxide to predict thermal conductivity and to permit more future engineering applications.
4. Compare nano aluminum oxide (Al_2O_3) to other nanomaterials such as silica and titanium dioxide (TiO_2), in order to establish the best additives for the various types of soils and their related environment.
5. Encourage more cooperation between geotechnical engineers, materials scientists, and energy planners to allow for the use of the findings to develop sustainable ground-source heat pump (GSHP) designs.
6. Assess the environmental and safety implications of nano aluminum oxide (Al_2O_3) before field-scale geotechnical applications, while ensuring compliance with appropriate engineering and material-handling practices.

6. ACKNOWLEDGMENTS

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7. DATA AVAILABILITY STATEMENT

No new experimental or simulation data were generated in this review. All data and findings discussed in this article were obtained from the published sources cited in the manuscript.

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