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*Review*

# Innovative Thermal Stabilization Methods for Expansive Soils: Mechanisms, Applications, and Sustainable Solutions

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**Abstract:** The thermal stabilization of expansive soils has emerged as a promising and sustainable alternative to conventional chemical stabilization methods, addressing the long-standing challenges associated with soil swelling and shrinkage. This review critically evaluates the mechanisms, applications, and advancements in thermal stabilization techniques, with a particular focus on both traditional approaches (e.g., kiln heating) and emerging innovations such as microwave heating. This study synthesizes recent research findings to assess how thermal treatment modifies the mineralogical, physical, and mechanical properties of expansive soils, reducing their plasticity and improving their strength characteristics. Comparative analysis highlights the advantages, limitations, and sustainability implications of different thermal methods, considering factors such as energy efficiency, scalability, and environmental impact. While thermal stabilization offers a viable alternative to chemical treatments, key challenges remain regarding cost, field implementation, and long-term performance validation. The integration of thermal treatment with complementary techniques, such as lime stabilization, is explored as a means to enhance soil stability while minimizing environmental impact. By addressing critical research gaps and providing a comprehensive perspective on the future potential of thermal stabilization, this review contributes valuable insights for researchers and engineers seeking innovative and sustainable solutions for managing expansive soils.

**Keywords:** expansive soils; thermal stabilization; swelling behavior; microwave heating; soil–water interactions

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## 1. Introduction

Expansive soils pose a significant challenge in geotechnical engineering due to their high susceptibility to volume changes in response to moisture variations. These soils, predominantly composed of swelling clays such as montmorillonite, undergo repeated cycles of expansion and contraction, leading to structural damage, foundation instability, and infrastructure failures [1]. In regions with pronounced seasonal variations in rainfall and temperature, the detrimental effects of expansive soils are particularly severe, resulting in costly repairs and maintenance. It is estimated that in the United States alone, annual damage to infrastructure due to expansive soil-related shrinkage and swelling exceeds USD 15 billion [2], with global losses surpassing USD 23 billion [3]. These economic and structural concerns underscore the pressing need for effective stabilization techniques to mitigate the adverse effects of expansive soils.

Various stabilization techniques have been employed to address expansive soil challenges, including chemical, mechanical, and thermal methods. Conventional chemical stabilization techniques, such as lime and cement treatment, have been widely used due

to their ability to improve soil strength and reduce swelling potential. However, these methods pose significant environmental concerns due to carbon emissions associated with cement and lime production [4]. Additionally, chemical treatments often require substantial curing time and may be ineffective in soils with high sulfate content, where adverse reactions can lead to secondary swelling. Mechanical stabilization techniques, such as soil reinforcement and compaction, offer immediate improvements but fail to provide long-term solutions, particularly in regions experiencing extreme weather conditions.

Thermal stabilization has emerged as a promising alternative, leveraging heat treatment to alter the mineralogical, physical, and mechanical properties of expansive soils [5–8]. However, despite its potential, existing thermal methods such as conventional kiln heating and electric resistance heating face challenges related to energy consumption, scalability, and long-term field validation. Newer innovations, such as microwave heating, offer energy-efficient alternatives but remain underexplored in terms of large-scale implementation. Given these limitations, there is a critical need to assess the effectiveness, sustainability, and practicality of thermal stabilization methods for expansive soils.

This review aims to systematically evaluate the mechanisms, applications, and challenges associated with the thermal stabilization of expansive soils. Specifically, it provides a comparative assessment of conventional and emerging thermal techniques, such as microwave heating, examining their effectiveness in modifying soil properties, reducing swelling potential, and enhancing long-term stability. Additionally, this study explores the integration of thermal methods with chemical stabilization to achieve improved geotechnical performance. The overarching goal is to provide comprehensive understanding of the feasibility and limitations of thermal stabilization as a sustainable engineering solution.

While previous research has demonstrated the fundamental effectiveness of thermal treatment in altering soil properties, critical gaps remain in the literature. Most studies focus on laboratory-scale experiments, with limited field trials assessing the durability and sustainability of thermally treated expansive soils under real-world conditions. There is a lack of systematic studies comparing the energy requirements and environmental footprint of thermal methods relative to conventional stabilization techniques. Despite its potential advantages, the efficiency, scalability, and optimal application parameters for microwave heating remain underexplored. Additionally, the combination of thermal methods with chemical or mechanical stabilization techniques requires further investigation to optimize performance and cost-effectiveness.

This review provides a unique contribution to the field by synthesizing and critically analyzing the latest advancements in the thermal stabilization of expansive soils. Unlike previous studies that focus on individual heating techniques, this work offers a comparative evaluation of both traditional and emerging thermal stabilization approaches, highlighting their advantages, limitations, and practical applications. Furthermore, it examines the environmental and economic feasibility of thermal methods and explores their integration with other stabilization techniques for enhanced performance. By addressing the identified research gaps, this review aims to guide future research and support the development of more effective, sustainable solutions for managing expansive soils in geotechnical engineering.

## 2. Background on Expansive Soils and Stabilization Methods

Expansive soils pose significant challenges to construction and infrastructure stability. The presence of minerals like montmorillonite exacerbates these issues, leading to structural damage such as subgrade deformation and slope collapse [9,10]. Various methods have been explored to mitigate the effects of expansive soils, including the use of industrial solid waste, chemical additives, and physical reinforcement techniques. Industrial solid waste, such as fly ash and ground granulated blast furnace slag, can improve soil properties

through mechanisms like cation exchange and pozzolanic reactions, enhancing compressive strength and reducing volume changes [11]. Chemical stabilization using lime and cement remains prevalent due to their effectiveness in reducing swelling potential, although environmental concerns persist [12,13]. Novel approaches, such as the application of pectin biopolymer or hydrophobic polyurethane foam, have shown promise in reducing both swelling and shrinkage in soils with high montmorillonite content [4,12]. Physical methods, including the use of sand and sand-lime piles, have demonstrated significant improvements in reducing the swelling potential of expansive clay soils, with effectiveness increasing alongside the replacement area ratio and lime content [13,14]. Additionally, intercalation and calcination techniques have been investigated to stabilize the clay interlayer structure, with aluminum intercalation and calcination at 200 °C yielding the best results in reducing soil expansiveness [15]. The integration of calcium-based stabilizer materials (CSMs) also offers a sustainable solution, leveraging pozzolanic properties to enhance soil stability through hydration and carbonation processes [16].

The stabilization of expansive clays through thermal treatment has a well-documented historical trajectory, rooted in the necessity to mitigate the adverse engineering properties of these soils for construction applications. Expansive clays present significant challenges in infrastructure development. These challenges often manifest as structural damage to buildings, pavements, and other engineered systems, resulting in substantial economic costs [17,18]. Over time, the stabilization of expansive soils has become a focal point of geotechnical research, with thermal treatment emerging as a scientifically validated and practical approach. This method involves exposing the clay to elevated temperatures, which induces alterations in its physical and chemical properties, thereby reducing its plasticity and swelling potential [19,20].

Extensive research has been conducted to evaluate the effects of thermal treatment on expansive clays, particularly at temperatures approximating 600 °C. Studies have demonstrated that such heating significantly enhances key soil properties, including the maximum dry density and California Bearing Ratio (CBR), while concurrently reducing plasticity and swelling tendencies [20]. These improvements render the treated clay more suitable for use as fill material in construction projects. Furthermore, thermal stabilization offers environmental benefits by reducing the need for the extensive excavation and transportation of spoil materials, thereby minimizing the ecological footprint of construction activities [20]. At a microstructural level, heating induces transformative changes in clay minerals, such as the collapse of kaolinite and modifications to montmorillonite, which contribute to the overall stability of the soil [19].

While thermal treatment of expansive clays remains primarily a subject of rigorous scientific investigation, its large-scale practical implementation faces significant challenges, including high energy costs, environmental impacts, and limited documentation of long-term performance. The scientific value of this research lies in advancing our understanding of clay mineral behavior under thermal conditions, though its application as an engineering solution requires further validation, particularly regarding cost-effectiveness and sustainability. The thermal treatment process of expansive clays involves intricate interactions between heat, moisture, and the mineralogical structure of the clay, which have been extensively modeled to predict soil behavior under varying thermal and hydraulic conditions [21,22]. These models provide critical insights into the thermal consolidation and swelling behavior of clays, facilitating the design of stable and durable structures on expansive soils [7,23]. The historical evolution of thermal stabilization techniques underscores their significance in geotechnical engineering and highlights their potential for further innovation in soil stabilization methodologies.

The use of heat to modify clay properties is not a novel concept; its origins can be traced back to ancient civilizations, where the firing of clay at high temperatures was employed to produce durable ceramics and construction materials. Archeological evidence, such as the thermoluminescent dating of ancient pottery, indicates that firing temperatures around 800 °C were commonly achieved in antiquity [24]. This process not only hardened the clay but also initiated chemical transformations, such as the oxidation of iron compounds, which enhanced the material's strength and esthetic qualities [25]. The cultural and technological significance of clay firing is evident in the Neolithic period, where specific techniques, including the use of temper materials like grog and calcite, were developed to produce pottery with enhanced thermal and mechanical properties [26]. These advancements reflect an early understanding of material science and the adaptation of thermal processes to meet societal needs.

Modern scientific analyses of ancient fired clays have provided valuable insights into the thermal history and technological capabilities of early societies. Techniques such as magnetic measurements and structural refinement methods have elucidated the complex changes that occur in clay minerals during heating. For instance, repeated thermal exposure has been shown to stabilize the magnetic properties of clays, making them useful for archaeomagnetic studies [25,27]. Additionally, structural analyses have revealed significant alterations in clay minerals, such as the collapse of kaolinite structures at elevated temperatures, further emphasizing the transformative effects of thermal treatment [19]. These findings not only enhance our understanding of historical technologies but also inform contemporary practices in ceramic and geotechnical engineering.

These diverse strategies underscore the importance of selecting appropriate treatment techniques based on specific soil conditions and environmental considerations, providing a comprehensive framework for addressing the challenges posed by expansive soils in engineering applications [28,29]. Figure 1 shows several methods utilized for stabilizing expansive soils.

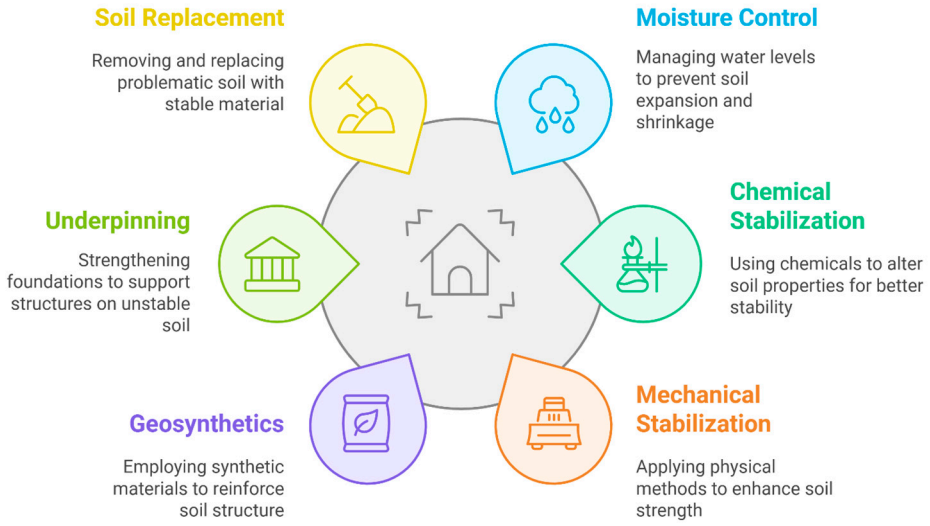



**Figure 1.** Methods for stabilizing expansive soils.

## 3. Mineralogy and Composition

### *3.1. Clay Minerals Responsible for Expansiveness*

The expansive behavior of soils is fundamentally linked to the presence of certain clay minerals, among which smectites are the most influential. Montmorillonite, a well-known member of the smectite group, is particularly notorious for its role in soil expansiveness. These minerals exhibit a distinctive 2:1 layered structure, characterized by two tetrahedral

silica sheets flanking a central octahedral alumina sheet. This unique arrangement creates an interlayer space that is highly susceptible to the adsorption of water molecules and cations. When exposed to moisture, water molecules infiltrate the interlayer regions, causing the lattice to expand significantly—a process known as swelling. Conversely, during drying or desiccation, the loss of water leads to shrinkage. This cyclical swelling and shrinkage, driven by changes in moisture content, can result in substantial volumetric changes in the soil, often posing significant challenges in geotechnical engineering applications [4,30].

Interestingly, the degree of expansiveness is not solely dependent on the presence of these minerals but also on their relative abundance and the specific environmental conditions to which the soil is subjected. For instance, in arid or semi-arid regions, where soils experience frequent wetting and drying cycles, the impact of smectite minerals can be particularly pronounced. Understanding these mechanisms is crucial for developing effective soil stabilization strategies, as the consequences of unchecked soil expansion can range from minor structural distortions to catastrophic foundation failures. While montmorillonite is often the primary culprit, it is worth noting that other clay minerals, such as illite and kaolinite, can also contribute to expansiveness, albeit to a lesser extent. Thus, a comprehensive analysis of soil mineralogy is essential for accurate risk assessment and mitigation in geotechnical projects [31].

### *3.2. Soil–Water Interactions*

Expansive soils interact with water through adsorption and desorption processes. Upon wetting, water molecules are attracted to the negatively charged surfaces of clay minerals, entering the interlayer spaces and causing the soil to swell. Conversely, during drying, water is released from these spaces, leading to shrinkage. The extent of these volume changes depends on factors such as clay mineral type, soil structure, and environmental conditions [32].

The double-layer theory explains the electrostatic interactions between clay particles and water. Clay particles possess negatively charged surfaces that attract cations and water molecules, forming an electrical double layer. The thickness of this layer influences the soil's swelling behavior; a thicker double layer results in greater repulsive forces between particles, leading to increased swelling. Understanding this theory is essential for predicting and managing the expansive behavior of soils [33,34].

The swelling characteristics of expansive soils are highly sensitive to the type of water they interact with. Experimental studies comparing various water types—including distilled water, flat water, treated wastewater, and seawater—have demonstrated that swelling percentages and surface heave tend to be less pronounced when using these alternatives compared to distilled water [35]. This is noteworthy because distilled water is typically the standard choice in laboratory testing, potentially leading to overestimations of swelling behavior in real-world scenarios where other water types are prevalent. These findings highlight the importance of considering specific water chemistry in practical applications, as it can significantly influence the soil's expansive response.

The Soil–Water Characteristic Curve (SWCC) plays a pivotal role in evaluating the hydraulic and mechanical characteristics of unsaturated expansive soils, offering insights into how these materials respond to fluctuations in moisture levels. Research indicates that SWCCs derived from both laboratory and field studies yield consistent results, particularly beyond the air entry value, making them a dependable resource for analyzing the properties of expansive soils in specific regions [36]. However, it is important to note that the volumetric changes inherent to expansive soils can profoundly influence the SWCC. Failing to account for these changes may result in inaccuracies, such as an overestimation of the soil's volumetric water content [37].

This relationship between soil volume and moisture dynamics underscores the need for the careful interpretation of SWCC data, especially in geotechnical applications where precise predictions of soil behavior are essential. By integrating these considerations, engineers and researchers can better address the challenges posed by expansive soils in both theoretical and practical contexts.

## 4. Factors Affecting Expansiveness

Figure 2 summarizes the factors influencing soil expansiveness. The expansiveness of soils is influenced by a combination of soil properties, environmental factors, and stress conditions [38,39]. Key soil properties include clay mineralogy, with smectites exhibiting the highest swelling potential, followed by illites and kaolinites [40,41]. Additionally, the soil fabric plays a role, as randomly arranged particles tend to swell more than oriented ones, and higher dry density generally reduces swelling. Environmental factors such as moisture content and its fluctuations, driven by climate, groundwater, drainage, and vegetation, significantly impact the shrink–swell behavior of soils [42,43]. Seasonal variations in moisture, improper drainage, and the influence of vegetation on moisture distribution contribute to volume changes. The state of stress within the soil, including applied loads and overburden pressure, also affects its potential for swelling [39]. Furthermore, properties such as the plasticity index, liquid limit, clay content, and measurements like the Coefficient of Linear Extensibility (COLE) and free swell tests are instrumental in assessing and quantifying soil expansiveness [38].

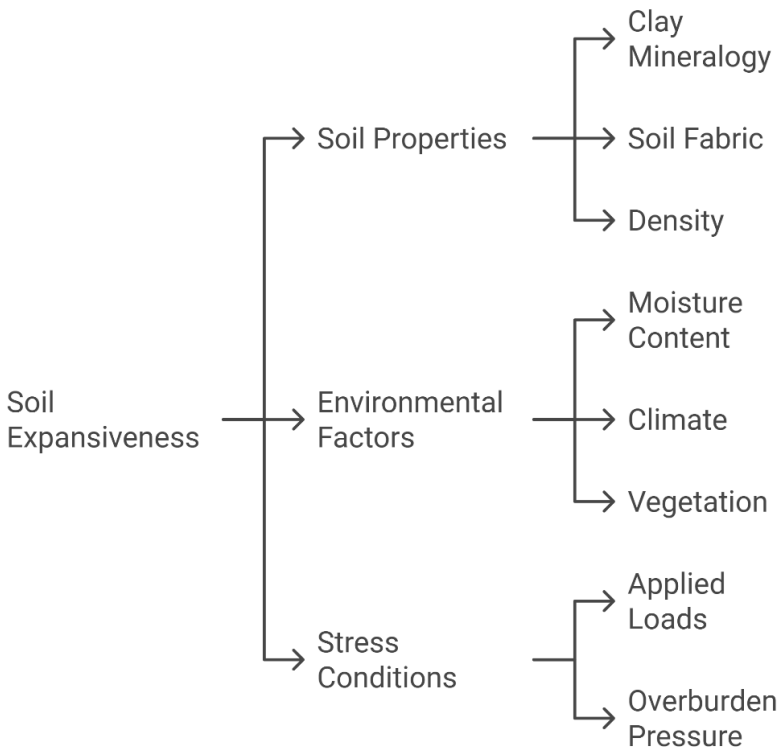



**Figure 2.** Factors influencing soil expansiveness.

Climate significantly influences the behavior of expansive soils by affecting the depth of the water table and the soil moisture active zone—the portion of the soil profile experiencing major seasonal moisture variations [43,44] (see Figure 3). In humid regions, a shallow water table maintains consistent soil moisture, reducing expansion issues. Conversely, arid regions often have deep water tables, leading to significant moisture fluctuations in surface soils and increased expansiveness. Understanding the depth of the active zone is crucial for foundation engineering, as it guides the minimum depth for pier placement

and is essential for calculating swell potential [44]. Typically, determining the active zone's thickness involves long-term heave measurements up to about 5 m below the surface [45]. Therefore, understanding these factors is crucial for predicting and managing the behavior of expansive soils effectively.

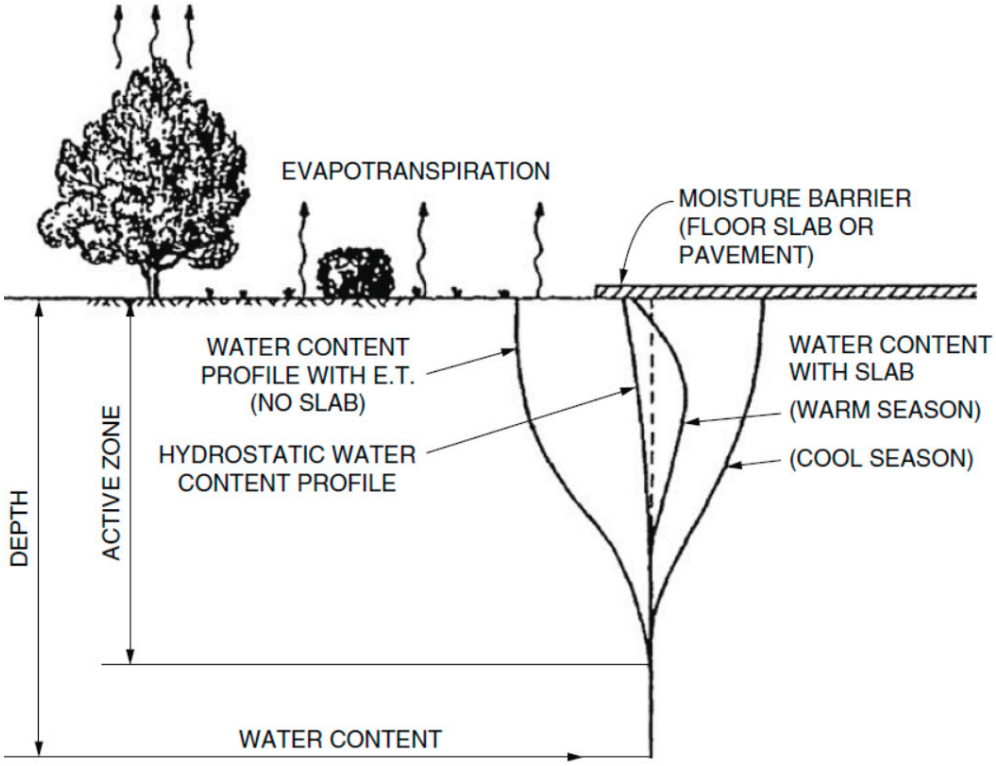



**Figure 3.** Illustration depicting moisture content in the active zone with and without the presence of a moisture barrier (adapted from [44]).

## 5. Thermal Properties of Expansive Soils

Expansive soils, characterized by their significant volume changes in response to moisture variations, exhibit distinct thermal properties that are crucial in geotechnical engineering applications. The primary thermal properties of interest are thermal conductivity, specific heat capacity, and thermal diffusivity. Thermal conductivity (λ) measures the soil's ability to conduct heat, specific heat capacity (c) indicates the amount of heat required to raise the temperature of a unit mass by one degree Celsius, and thermal diffusivity (α) reflects the rate at which temperature changes propagate through the soil [46,47].

The mineralogical composition of expansive soils, particularly the presence of clay minerals such as smectite and montmorillonite, significantly influences these thermal properties. Soils rich in smectite minerals tend to have higher specific surface areas, which can affect heat transfer mechanisms within the soil matrix [46,48]. Additionally, the moisture content of expansive soils plays a pivotal role; as moisture content increases, both thermal conductivity and specific heat capacity generally increase due to the higher thermal conductivity of water compared to air [46,47]. This relationship underscores the importance of considering both mineralogical composition and moisture content when evaluating the thermal behavior of expansive soils.

The thermal treatment of soils containing sulfates, gypsum, or organic matter presents distinct challenges and behaviors that warrant careful consideration [49–51]. In sulfate-rich soils, thermal activation accelerates persulfate decomposition, generating sulfate radicals that influence the soil's chemical properties [52]. The presence of gypsum in soils subjected to thermal treatment can lead to dehydration and structural alterations, potentially affecting the soil's engineering properties [52,53]. Furthermore, thermal conductivity in sulfate-containing soils exhibits dynamic changes with temperature variations, particularly during phase transitions [54]. Of particular significance is the behavior of organic matter under thermal treatment, where exothermic reactions during thermal oxidation can influence soil stability [55]. These organic components may form complexes that affect contaminant mobility and treatment efficacy, as demonstrated in studies of mercury-contaminated soils [56].

Understanding these thermal properties is essential for analyzing the impact of heat treatment on expansive soils. Heat treatment can alter the mineralogical structure and moisture content, thereby affecting the soil's thermal behavior and its engineering performance [6]. The accurate characterization of these properties enables engineers to predict and mitigate potential issues arising from temperature-induced volume changes in expansive soils [47].

## 6. Effects of Extreme Heating on Expansive Soil Properties

The thermal treatment of expansive soils has gained attention as a method to mitigate their problematic behavior, particularly swelling, plasticity, and poor strength. Studies demonstrate that subjecting expansive soils to high temperatures induces significant physical, chemical, and mechanical changes, which can potentially stabilize these soils for engineering applications. Table 1 shows a summary of findings from studies investigating the effects of thermal treatment on expansive soils, including experimental methods, soil types, heating conditions, and key outcomes related to soil plasticity, swelling, and mechanical properties.

### *6.1. Swelling Behavior and Thermal Stabilization*

The swelling behavior of expansive soils is one of the primary concerns in geotechnical engineering. Wang et al. [7] employed thermal stabilization techniques using programmable furnace heating to assess swelling behavior under controlled conditions. Their research indicated that specific heating thresholds, such as 400 °C for kaolin and 600 °C for bentonite, effectively converted expansive soils into non-expansive ones by altering the clay mineral structure. Differential thermal analysis (DTA) highlighted irreversible changes in the crystal structure, suggesting that heating could serve as a long-term solution for swelling mitigation. However, they emphasized the necessity for systematic databases and the consideration of other influential factors, such as soil density and groundwater conditions, to optimize thermal stabilization techniques. The high energy costs associated with these methods remain a limiting factor for widespread adoption.

### *6.2. Changes in Physical and Chemical Properties*

The heating process not only alters the swelling potential but also significantly affects the physical and chemical properties of expansive soils. Li et al. [57] investigated the properties of expansive soils heated up to 140 °C. They observed rapid increases in mean particle diameter and density up to 100 °C, followed by stabilization or decline at higher temperatures. The thermal decomposition of free and bound water led to notable microstructural changes, influencing hydraulic and strength behaviors crucial for pollution prevention and engineering applications.

Kabubo et al. [20] extended the investigation to higher temperatures, heating black cotton soil to 600 °C. Their findings showed improved strength characteristics, with the maximum dry density (MDD) increasing by 15% and California Bearing Ratio (CBR) improving from 1 to 3. Furthermore, reductions in the plasticity index, linear shrinkage, and free swell by 30%, 27%, and 38%, respectively, demonstrated the effectiveness of thermal treatment in reducing plasticity and swelling potential. However, the study highlighted the need for cost comparisons and long-term field trials to validate the feasibility of large-scale applications.

### 6.3. Microwave Heating and Its Implications

Microwave heating has emerged as a promising alternative due to its efficiency and reduced environmental impact. The application of microwave irradiation has emerged as a promising advancement in geotechnical engineering, particularly for addressing the challenges posed by problematic soils such as expansive clays. A seminal investigation by Zhang et al. [58] (preprint) examined the long-term performance of expansive soils subjected to cyclic wetting and drying following microwave treatment. Their experimental program demonstrated that thermal modification through microwave exposure, particularly at temperatures above 300 °C, yielded substantial improvements in both compressive strength characteristics and volumetric stability. Through rigorous analysis of damage parameters across multiple scales, the researchers established a clear correlation between microstructural modifications induced by microwave treatment and enhanced mechanical properties. Most notably, specimens treated at 500 °C exhibited a remarkable 27-fold increase in compressive strength, accompanied by an almost complete suppression of expansion potential. These findings underscore the efficacy of microwave irradiation in mitigating moisture-induced instability in expansive soils, with significant implications for geotechnical infrastructure in problematic soil regions.

In a subsequent field-oriented investigation, Hu et al. [59] explored the practical feasibility of implementing in situ microwave treatment for the improvement of waste-derived clayey soils. Their experimental methodology involved the use of a microwave radiation system with a frequency of 2.45 GHz and a power of 1.25 kW. The soil model, constructed from clayey soil collected from Mulan Town, Chengdu, China, was exposed to continuous microwave irradiation for 72 h. The apparatus included a rectifier power supply, power control board, magnetron, BJ26 waveguide, quartz window, water pump, buzzer alarm, and thermocouples for temperature monitoring. The BJ26 waveguide antenna, simulated using COMSOL software, radiated microwave energy into the soil model, with the far-field radiation pattern resembling an ellipsoidal surface. To prevent microwave leakage, a layer of copper metal mesh was installed after the equipment setup. The soil model was divided into layers, each approximately 5 cm thick, and compacted before microwave exposure. Temperature measurements were taken at various distances from the waveguide port using thermocouples arranged symmetrically along the central axis of the model. The study demonstrated that the soil could be divided into three distinct regions based on the effects of microwave heating: the microwave heating area, the heat transfer area, and the unaffected area. The microwave heating area, located closest to the waveguide port, experienced the most significant temperature increase and soil property improvements, including enhanced mechanical strength and water stability. These results provide crucial insights into the practical implementation of in situ microwave stabilization techniques, with broader implications for sustainable soil improvement practices. Figure 4 illustrates the sample preparation method.

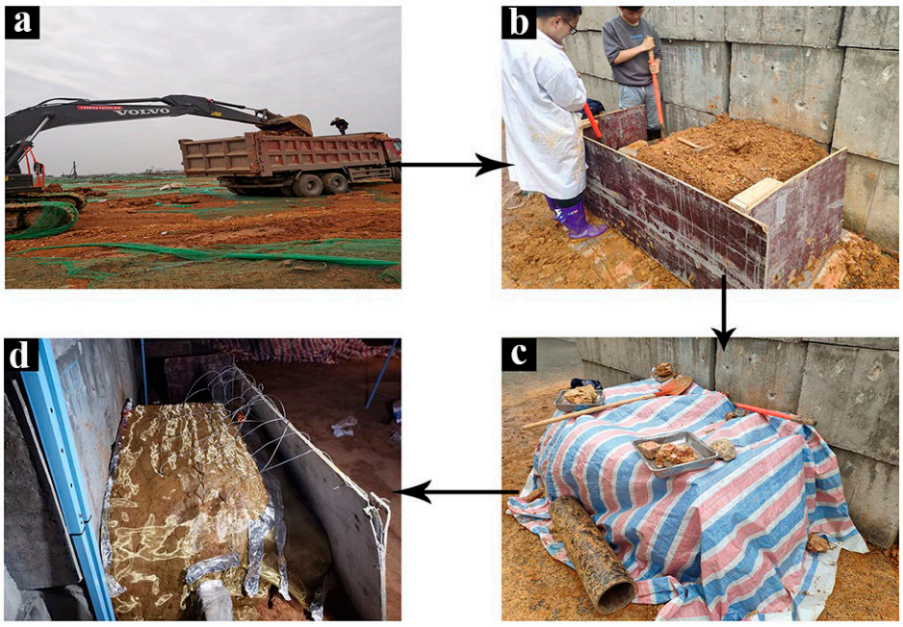



**Figure 4.** Construction process of the soil model [59]: (**a**) sampling, (**b**) filling, (**c**) stilling, and (**d**) molding.

Recent work by Yao et al. [8] has further elucidated the mechanisms through which microwave heating influences the swelling characteristics of expansive soils, focusing on samples obtained from Hefei, China. Their systematic investigation revealed that microwave exposure induces particle size redistribution toward coarser fractions, accompanied by significant alterations in fundamental soil properties including specific gravity and Atterberg limits. The experimental results demonstrated a marked reduction in both the free swelling ratio and vertical free swelling strain with increased duration of microwave exposure. These modifications were attributed to a complex series of physicochemical transformations, including the liberation of interlayer water molecules, mineral phase transformations, and fundamental changes in soil fabric. Their findings substantiate the effectiveness of microwave treatment as a time-efficient alternative to conventional thermal stabilization methods, particularly in contexts where the rapid modification of swelling potential is desired.

The effects of microwave heating on expansive soil properties are further illustrated in Figure 5a,b. Figure 5a depicts the changes in the liquid limit and plastic limit with increasing microwave heating time. As the heating duration extends, both the liquid and plastic limits decrease, indicating a reduction in the soil's ability to retain water and its plasticity. This suggests that microwave heating alters the soil's structure, making it less expensive and more stable. Figure 5b shows the change in the free swelling ratio with heating duration. The data indicate a consistent decline in the swelling ratio as the heating time increases, reinforcing the notion that microwave heating effectively mitigates the swelling characteristics of expansive soil. These findings underscore the potential of microwave heating as a method for soil stabilization, though careful consideration of heating parameters is essential to achieve desired outcomes. However, its application may be constrained by equipment costs and the need for precise control over heating durations.

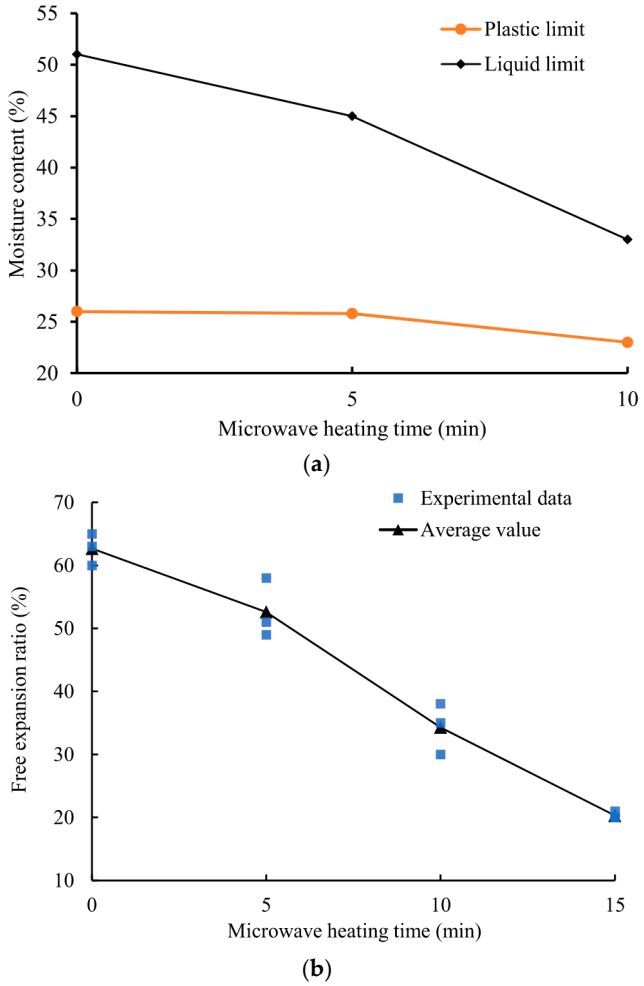



**Figure 5.** Effect of microwave heating on expansive soil properties [8]: (**a**) change in liquid limit and plastic limit with heating duration, (**b**) change in free swelling ratio with heating duration.

### *6.4. High-Temperature Effects on Soil Strength and Plasticity*

Abu-Zreig et al. [60] investigated clayey soils subjected to heating up to 400 °C. They observed substantial reductions in liquid and plastic limits, swelling pressure, and unconfined compressive strength, while the maximum dry density increased slightly. Notably, heating above 100 °C resulted in significant property changes, with reductions of up to 100% in swelling pressure and unconfined compressive strength. These findings highlight the potential of heat treatment as an effective stabilization strategy, albeit with energy consumption as a critical constraint.

Similarly, Rahil et al. [61] analyzed the effects of heating borehole spacing on soil plasticity, demonstrating that heating significantly reduced the plasticity index and liquid limit, particularly for soils with higher bentonite content. The study revealed a nonlinear relationship between borehole spacing and heating effectiveness, suggesting that the optimization of heating patterns could enhance stabilization outcomes.

### *6.5. Combined Thermal and Chemical Stabilization*

Incorporating thermally treated clay with other stabilizing agents, such as lime, has shown significant promise in enhancing the properties of expansive soils. Al-Swaidani et al. [62] conducted a comprehensive study demonstrating that a combination of 20% thermally treated clay and 6% lime effectively reduced swelling pressure and linear shrinkage by more than 85%. This substantial reduction in swelling and shrinkage behaviors highlights the synergistic effects of combining thermal and chemical stabilization methods. X-ray

diffraction (XRD) analysis played a crucial role in understanding the underlying mechanisms, revealing that the thermal treatment transformed clay minerals into an amorphous phase at elevated temperatures. This transformation not only reduced the soil's expansive nature but also enhanced its pozzolanic activity, leading to improved soil strength and stability. The findings suggested that the integration of thermal and chemical stabilization techniques can offer a robust solution for mitigating the challenges posed by expansive soils, particularly in engineering applications where soil stability is paramount. However, further research is needed to optimize the proportions of thermally treated clay and lime, as well as to explore the long-term performance and durability of such stabilized soils under various environmental conditions.

**Table 1.** Summary of studies on thermal treatment effects on expansive soils.

| | Reference | Methods Used | Type of Tested Soil | Application Method of Heating | Main Results |
|---|---|---|---|---|---|
| 1 | Rahil et al. [61] | Laboratory-prepared soils mixed with 20–60% bentonite, heated at 400 °C for 6 h using electric heaters at varying borehole spacings (4.16 d, 6.25 d, and 8.33 d), where "d" represents the diameter of the boreholes. | Expansive soil (Kut area, Iraq), bentonite mix | Electric cartridge heaters in boreholes (13.5 mm diameter), maintained at 400 °C for 6 h, followed by 24 h cooling. | - Borehole spacing significantly impacted plasticity—wider spacings increased the liquid limit and plastic limit. Plasticity index rose at a rate of ~1.6 per spacing increment—results demonstrated that heating effectively modified expansive soil plasticity, with smaller spacing yielding better results. |
| 2 | Yao et al. [8] | - Industrial microwave oven (2.45 GHz, 0–6 kW) heated at 305 °C (5 min), 470 °C (10 min), 680 °C (15 min)—tests included specific gravity, liquid/plastic limits, and free swelling ratio. | Expansive soil (Hefei, China), rich in montmorillonite | Soil heated in a quartz crucible at 4 kW for three durations (5–15 min). Structural water escape and dehydroxylation induced chemical changes. | - Swelling reduced significantly with increased heating time—specific gravity initially rose, then declined—liquid/plastic limits decreased consistently—microwave heating altered particle structure, transitioning from fine to coarse particles and improving soil stability. |
| 3 | Joshi et al. [63] | - Thermogravimetric analysis, porosimetry, and compressive strength tests—samples were heated at 300 °C, 400 °C, 500 °C, 600 °C, and 700 °C in a muffle furnace to assess pore distribution, void ratio, and strength. | Kaolinite, bentonite, Western Beaufort Sea clay | Oven-dried samples heated in a muffle furnace at 3 °C/min, held at target temperature for 2 h, cooled overnight. | - Strength increased up to 700 °C due to dehydroxylation, with bentonite showing the highest improvement—minimal pore size changes were observed—compressive strength increased by ~300%, but changes varied between clay types, highlighting the soil-specific nature of heat treatment. |

**Table 1.** *Cont.*

| | Reference | Methods Used | Type of Tested Soil | Application Method of Heating | Main Results |
|---|---|---|---|---|---|
| 4 | Wang et al. [7] | - Thermal stabilization using a programmable furnace, heated at 100 °C, 200 °C, 300 °C, 400 °C, 500 °C, 600 °C—swelling measured via modified consolidation apparatus. Differential thermal analysis (DTA) conducted. | Edgar Plastic Kaolin (EPK) and Western Bentonite (WB) | Electric furnace, incremental heating to avoid shrinkage cracking. Swelling measured post heating. | - Swelling reduced significantly above 400 °C. EPK became non-expansive at 400 °C, while WB required heating to 600 °C—the study provided critical thresholds for designing effective stabilization methods for expansive soils. |
| 5 | Kabubo et al. [20] | - Black cotton soil (Kenya) heated to 600 °C for 2 h—tests included CBR, plasticity index, compaction, linear shrinkage, and swelling potential. | Black cotton soil (Mwihoko area, Kenya) | Soil heated in a closed electric kiln, cooled to room temperature to assess reversibility of changes. | - Soil transitioned to non-expansive and non-plastic states—swelling potential and plasticity index reduced significantly—maximum dry density increased by ~15%—chemical composition changes (increased aluminum/iron oxides) were observed, resulting in irreversible structural modifications suitable for engineering applications. |
| 6 | Li et al. [57] | - XRD, TG/DTA, and direct shear tests were conducted—laser particle size analysis was used to assess physical and chemical changes in expansive soil samples—the heating temperatures were 20 °C, 40 °C, 60 °C, 80 °C, 90 °C, 100 °C, 120 °C, and 140 °C | Expansive soil (Hanzhong, Shanxi Province, China) | Controlled heating via Netzsch analyzer under dry nitrogen atmosphere. TG/DTA analyzed water loss and microstructural changes. | - Mean particle diameter increased significantly up to 100 °C, with structural stability improving due to water loss—shear strength and density improved, with notable microstructural transformations, enabling better pollution prevention and soil stabilization applications. |
| 7 | Al-Swaidani et al. [62] | - XRD, modified Chapelle test, and Atterberg limits—thermally treated clay at 450 °C, 650 °C, 850 °C mixed with untreated expansive soil to assess pozzolanic activity and engineering properties. | Expansive clayey soil (Syria, 3 sites) | Clay heated for 3 h at different temperatures, and then blended with untreated soil (0%, 10%, 20% replacement). | - Plasticity index reduced by ~60% with 20% thermally treated clay—combined with 6% lime, swelling pressure reduced by ~85%—optimal stabilization observed at 850 °C due to enhanced pozzolanic activity. |

**Table 1.** *Cont.*

| | Reference | Methods Used | Type of Tested Soil | Application Method of Heating | Main Results |
|---|---|---|---|---|---|
| 8 | Zhang et al. [58] (preprint) | - Macroscopic and microscopic damage parameter analysis—unconfined compressive strength tests—free expansion rate tests—SEM | Expansive soil | Microwave irradiation at various temperatures (200–500 °C) | - Increased compressive strength (up to 27 times at 500 °C)—reduced expansion rate (to nearly 0 at 500 °C)—altered soil microstructure leading to improved water resistance and strength-mitigation of dry–wet cycle effects. |
| 9 | Hu et al. [59] | - Temperature and moisture content monitoring—Vickers hardness tests—free swelling rate tests—water stability tests—SEM, XRD | Wasted clayey soil | In situ microwave irradiation (2.45 GHz, 1.25 kW). | - Distinct heating zones: microwave heating, heat transfer, unaffected—improved mechanical properties and water stability in the microwave heating area—unique moisture distribution pattern due to microwave influence. |

## 7. Technical and Practical Implementation Challenges

The application of thermal treatment for stabilizing expansive soils presents several technical and practical challenges that must be addressed to transition these methods from experimental to widespread engineering practice. While studies have demonstrated the efficacy of heating expansive soils in improving their physical, chemical, and mechanical properties, factors such as energy consumption, environmental impact, and the complexity of in situ implementation pose significant barriers.

### *7.1. Energy Intensity and Cost*

One of the primary challenges associated with thermal stabilization is its high energy requirement. Wang et al. [7] emphasized that heating expansive soils to the temperatures necessary for stabilization, such as 400 °C for kaolin and 600 °C for bentonite, incurs substantial energy costs. This is particularly significant for large-scale applications where extensive heating infrastructure and prolonged energy use are required. Similarly, Kabubo et al. [20] highlighted that while heating black cotton soil to 600 °C improved its engineering properties, the associated energy consumption makes this approach less feasible compared to traditional stabilization methods like lime treatment or soil replacement.

### *7.2. Environmental Concerns*

The environmental impact of thermal stabilization methods, particularly due to greenhouse gas emissions from fossil fuel-based heating, is a critical concern. Kabubo et al. [20] utilized a closed electric kiln to minimize emissions during the heating process, but the approach still relied on significant energy input. The environmental cost of large-scale heating may outweigh its benefits, especially in contexts where sustainability is a priority.

Microwave heating has been suggested as a cleaner alternative with reduced emissions. Yao et al. [8] demonstrated the efficacy of microwave heating in altering the swelling properties of expansive soils while highlighting its potential as an environmentally friendly

option. However, the cost and complexity of deploying microwave technology for large-scale soil stabilization remain significant barriers.

### 7.3. Variability in Soil Behavior

The heterogeneity of expansive soils presents a challenge in standardizing thermal treatment techniques. Rahil et al. [61] demonstrated that soils with varying bentonite content respond differently to heating, requiring adjustments in heating duration and intensity. Similarly, Wang et al. [7] noted that soil density, the degree of saturation, and electrolyte concentration can significantly influence the effectiveness of thermal stabilization. The lack of a comprehensive database encompassing a wide range of soil types and environmental conditions complicates the design and implementation of thermal treatment protocols.

### 7.4. Limitations in Practical Implementation

The in situ implementation of thermal stabilization methods faces logistical challenges. The controlled heating of expansive soils in laboratory conditions, as described by Abu-Zreig et al. [60] and Li et al. [57], is difficult to replicate in the field. Maintaining consistent temperatures, ensuring uniform heating, and managing soil cooling post treatment are complex tasks that require specialized equipment and expertise.

Microwave heating, while promising, poses its own challenges. Yao et al. [8] noted the difficulty in scaling microwave technology for large projects, as the equipment required for uniform soil heating is expensive and requires significant power infrastructure. Furthermore, the transition of treated soils from fine to coarse particles during microwave heating may alter their load-bearing characteristics, necessitating careful assessment of post-treatment soil performance.

While laboratory investigations have yielded encouraging results, the translation of microwave heating technology to field-scale soil improvement applications encounters several formidable challenges. Chief among these is the inherent limitation in microwave penetration depth, a constraint well documented in the recent literature. Hu et al. [59] observed that effective treatment zones typically extend only to approximately 20 cm below the surface, primarily due to the progressive attenuation of microwave energy during soil mass penetration. This attenuation phenomenon exhibits complex dependencies on soil parameters including moisture content, bulk density, and mineralogical composition. The development of practical field applications thus necessitates innovative solutions to overcome these energy transmission and distribution constraints. Additionally, the substantial power requirements and associated economic implications of large-scale microwave generation systems present significant barriers to widespread implementation. Although the fundamental efficacy of microwave treatment has been well established through the works of Yao et al. [8] and Zhang et al. (preprint) [58], their experimental frameworks employed laboratory-scale apparatus that may not readily translate to field conditions without considerable investment in specialized equipment and supporting infrastructure.

A particularly challenging aspect of field implementation stems from the inherent heterogeneity of natural soil deposits. The spatial variability in soil characteristics, including moisture distribution, density gradients, and mineralogical composition, can result in non-uniform heating patterns and consequently inconsistent improvement across the treatment volume. This heterogeneity is further exacerbated by the presence of field obstacles such as cobbles, organic matter, and buried infrastructure, which can significantly disrupt microwave energy distribution patterns. Moreover, the long-term durability of microwave-treated soils under dynamic environmental conditions, particularly in response to groundwater fluctuations and seasonal temperature cycles, remains inadequately characterized. While laboratory studies consistently demonstrate enhanced mechanical properties

and reduced expansion potential, the complex interactions between stabilized zones and the surrounding soil matrix under field conditions warrant more detailed investigation.

Critical advancement of this technology toward practical implementation requires concentrated research efforts in several key areas. Priority should be given to developing more energy-efficient microwave generation systems, improving penetration depth through novel wave guide designs, and conducting comprehensive field trials under varied geological conditions. These investigations must address not only the immediate technical challenges but also consider the broader implications for construction methodology, quality control procedures, and long-term performance monitoring protocols. The transition from laboratory concept to established geotechnical practice demands a thorough understanding of these multifaceted challenges and their practical solutions, supported by rigorous field validation and performance documentation.

### *7.5. Long-Term Performance and Uncertainty*

The long-term stability and performance of thermally treated expansive soils remain uncertain. Kabubo et al. [20] raised concerns about the potential reversal of treated soil properties over time and emphasized the need for long-term field trials. Similarly, Al-Swaidani et al. [62] noted that while combining thermally treated clay with lime significantly reduced swelling pressure and linear shrinkage, the durability of these improvements under varying environmental conditions requires further investigation.

### *7.6. Infrastructure and Heating Patterns*

The use of borehole heating, as explored by Rahil et al. [61], introduces additional challenges related to infrastructure and heating patterns. Optimizing borehole spacing and ensuring uniform heat distribution are critical for achieving effective stabilization. Non-uniform heating can lead to uneven soil properties, potentially compromising structural stability. The study found a nonlinear relationship between borehole spacing and heating effectiveness, indicating the need for precise design and implementation.

### *7.7. Economic and Social Considerations*

Cost comparisons between thermal treatment and conventional methods, such as excavation and replacement or chemical stabilization, remain a key factor influencing the adoption of thermal stabilization. Kabubo et al. [20] highlighted that thermal treatment, while effective, may not be economically competitive in regions with limited resources or high energy costs. Furthermore, the social acceptability of deploying energy-intensive methods in environmentally sensitive areas could limit their application.

## 8. Extreme Heating Techniques for Soil Stabilization

The application of extreme heating techniques for stabilizing expansive soils represents a fascinating intersection of thermodynamics and geotechnical engineering. These methods, which fundamentally alter both physical and chemical properties of problematic soils, have evolved from relatively simple approaches to sophisticated technological interventions. What makes these techniques particularly interesting is their ability to induce permanent changes in soil behavior, effectively transforming troublesome expansive materials into more manageable geotechnical mediums.

Among these approaches, the practice of burning fuels in boreholes stands out as one of the more dramatic interventions. This technique, pioneered by Beles and Stănculescu [64] and further developed by Litvinov [65], can generate impressive temperatures approaching 800 °C. At such extreme temperatures, the soil undergoes profound transformations—from the obvious dehydration of clay minerals to more complex processes like mineral structure alterations and sintering. The effectiveness of this method, particularly for slope

stabilization and bearing capacity enhancement, stems from these irreversible mineralogical changes.

Electric heating techniques, while less intense, offer more precise control over the treatment process. Park et al. [66] demonstrated that using pipe heaters to achieve temperatures up to 110 °C can significantly enhance soil properties. Their findings were particularly striking: soil bearing capacities increased more than threefold after treatment, accompanied by substantial vapor emission during the heating process. What is especially noteworthy is the formation of a completely sintered zone extending approximately 20 cm around the electric heater—a clear indication of permanent soil modification. The relationship between heating temperature, duration, and soil improvement is not linear, though; the most dramatic changes occur when temperatures exceed 100 °C, coinciding with the point of water vaporization.

Perhaps the most technologically sophisticated approach is microwave heating, which has garnered increasing attention in recent years. This method can achieve temperatures up to 680 °C, but what sets it apart is its unique interaction with soil water molecules. Recent studies have shown that microwave heating's efficiency stems from its ability to directly couple with water molecules, resulting in rapid and relatively uniform heating throughout the treated volume [8,67]. This characteristic makes it particularly effective for localized treatment applications where precise control over the treated zone is crucial.

The selection of an appropriate heating method is not straightforward; it requires careful consideration of numerous factors including project requirements, soil conditions, and practical constraints. Each technique brings its own set of advantages and limitations. For instance, while borehole burning might be more economical for large-scale applications, microwave heating could be more suitable for sensitive sites requiring precise control. Electric heating, meanwhile, often represents a middle ground, offering good control while remaining relatively cost-effective.

What is particularly intriguing about these thermal stabilization methods is their long-term effectiveness. Unlike some chemical stabilization techniques that might degrade over time, thermal modifications typically result in permanent changes to soil structure and mineralogy, providing lasting improvements to geotechnical properties. However, this permanence also means that careful preliminary testing and modeling are essential to ensure the desired outcomes are achieved.

## 9. Conclusions

The thermal stabilization of expansive soils presents a compelling approach for mitigating the challenges posed by their volumetric instability. This review highlights the significant potential of these techniques, while also acknowledging the complexities involved in their practical implementation. Based on the current state of research, the following conclusions can be drawn:

1. Efficacy of Thermal Treatment:
    - Thermal treatment, whether through conventional heating or innovative methods like microwave irradiation, induces profound and often irreversible changes in expansive soils.
    - These changes include the transformation of clay mineral structures (e.g., conversion of smectites), alterations in soil fabric, and improvements in key engineering properties like compressive strength and swelling potential.
2. Challenges and Limitations:
    - Energy Intensity and Cost: Many thermal methods, especially those relying on traditional fuel combustion, are energy-intensive, raising economic and environ-

mental concerns. Scalability and cost-effectiveness of microwave heating remain under investigation.
- Soil Heterogeneity: The inherent variability in natural soil deposits complicates the standardization of treatment protocols and necessitates site-specific adjustments.
- Depth of Penetration: Achieving uniform treatment at depth, particularly with microwave heating, remains a challenge due to energy attenuation.
- Long-Term Performance: The long-term durability of thermally treated soils under various environmental conditions requires further research and field validation.

3. Future Research Directions:
   - Optimization of Energy Efficiency: Exploring more energy-efficient heating methods and optimizing existing techniques are crucial for practical viability.
   - Refinement of Application Techniques: Developing robust field implementation strategies that address soil heterogeneity and ensure uniform treatment.
   - Comprehensive Field Validation: Conducting long-term field trials and monitoring programs to assess the durability and performance of treated soils under real-world conditions.
   - Life-Cycle Assessments: Evaluating the environmental and economic impacts of thermal stabilization across the entire project lifecycle.
4. Multidisciplinary Approach:
   - Successfully transitioning thermal stabilization from a promising concept to widespread practice will require collaborative efforts, integrating insights from geotechnical engineering, materials science, and environmental engineering.

In closing, thermal stabilization offers a viable pathway toward more resilient and sustainable construction practices in expansive soil regions. By addressing the identified challenges and pursuing focused research, the geotechnical engineering community can unlock the full potential of these techniques, paving the way for more effective and responsible management of problematic soils in future infrastructure projects. The convergence of these efforts will be paramount in ensuring the long-term success and broader adoption of thermal stabilization methodologies.

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