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Microstructural and mechanical characterization of expansive soils for sustainable stabilization purposes

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Abstract

Expansive soils pose significant challenges due to their high potential for volume changes, leading to structural damages. This study aims to comprehensively characterize the microstructural and mechanical properties of expansive soils to facilitate selecting appropriate stabilization techniques. Advanced analytical methods including X-ray Diffraction (XRD), Scanning Electron Microscopy with Energy Dispersive X-ray (SEM-EDX), Thermogravimetric Analysis (TGA), Differential Thermal Analysis (DTA), Fourier Transform Infrared (FTIR) spectroscopy and mechanical tests were employed. XRD analysis identifies and quantifies swelling clay minerals influencing expansive behaviour. SEM-EDX provides insights into particle morphology, microstructure, and elemental composition. TGA and DTA reveal thermal properties and phase transitions. FTIR offers insights into organic functional groups and molecular interactions. Mechanical tests evaluate strength, compressibility and volume change characteristics. By comprehensively characterizing microstructural attributes and mechanical behaviour of expansive soils, this research enables informed selection of stabilization techniques to mitigate adverse effects on infrastructure. This findings underscore leveraging advanced analysis to tailor stabilization strategies per specific soil characteristics, enhancing effectiveness and sustainability of ground improvement solutions.

1. Introduction

Expansive soils pose a significant challenge in the field of geotechnical engineering due to their high potential for volume changes in response to variations in moisture content. These problematic soils can undergo substantial swelling when exposed to water and significant shrinkage when dried, leading to severe structural damages and instability issues in various civil engineering projects [4, 8]. The presence of expansive clay minerals, such as montmorillonite and vermiculite, within the soil matrix is the primary cause of this undesirable behaviour [4]. The abundance of expanded crystalline form clay elements pertaining to the smectite group, with montmorillonite representing a vital component of this family, distinguish expansive soils [11].

The detrimental effects of expansive soils can be observed in a variety of construction projects, including building foundations, roads, embankments, and even underground infrastructure. The volume changes experienced by these soils can result in differential settlements, cracks in structures, and distortion of pavement systems, compromising the structural integrity and serviceability of the built environment [4, 8 & 49]. Furthermore, the challenges posed by expansive soils can lead to significant maintenance costs and, in some cases, the complete failure of construction projects, underscoring the critical need for effective stabilization techniques.

Expansive soils are commonly found in arid and semi-arid regions, where seasonal changes in rainfall and temperature can trigger dramatic volume fluctuations [8]. This cyclic swelling and shrinkage behaviour poses a significant challenge to civil engineers, as the resulting deformations can cause extensive damage to structures and infrastructure. The severity of the problems associated with

expansive soils varies depending on factors such as the mineralogical composition, plasticity, and degree of saturation of the soil.

To address the challenges posed by expansive soils, researchers have employed various characterization techniques to gain a comprehensive understanding of their mineralogical composition, microstructural features, and thermal behaviour. The application of advanced analytical methods, such as X-ray diffraction (XRD), scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM-EDAX), and thermal analysis (TGA/DTA), has provided valuable insights into the underlying mechanisms responsible for the swelling and shrinkage phenomena [1, 5, 10, 15, 19 & 40]. The XRD analysis of expansive soil samples has revealed the dominant presence of swelling clay minerals, such as montmorillonite and vermiculite, and the relative abundance of these expansive components has been quantified [1, 7, 17 & 27]. The SEM-EDAX investigations have complemented the XRD findings by providing insights into the microstructural features and elemental composition of the soils, directly linking the observed morphological characteristics to the presence of specific clay minerals [15, 35 & 40]. These were classified into numerous groups of clays depending upon their stratified structure, which includes montmorillonite, saponite, mica, serpentine, talc, sepiolite, and others [35, 44 & 50]. Furthermore, the clays' sorption capabilities are determined by its substantial porosity as well as their surface area components [2]. Montmorillonite clay possesses the biggest surface area with the best capability for exchanging cations within natural clay minerals. It pursuant to the estimate, the global market cost of montmorillonite clay will be roughly 1303 million USD in 2022 [14]. Furthermore, the thermal analysis techniques have shed light on the dehydration and dehydroxylation processes occurring within the clay mineral structure, which are closely associated with the volume change behaviour of the expansive soils [1, 19 & 40].

While the comprehensive characterization of expansive soils using these advanced techniques has significantly advanced our understanding of their problematic behaviour, the development of effective stabilization methods remains a critical challenge. Traditional stabilization approaches, such as lime or cement treatment, have been widely employed to mitigate the issues associated with expansive soils [4, 18, 21, 24 & 39]. These methods aim to modify the soil's physical, chemical, and mineralogical properties, leading to a reduction in the swelling potential and an improvement in the overall engineering performance. However, the long-term durability and environmental concerns associated with cement production have prompted the exploration of alternative stabilization techniques [37, 54]. The understanding gained in the subject of clay mineralogy has also proved useful in genetic and taxonomic investigations of soil [38]. The present study aims to comprehensively characterize two expansive soil samples, denoted as Soil A and Soil B, using advanced analytical techniques, including XRD, SEM-EDAX, and TGA/DTA. The detailed investigation of the mineralogical composition, microstructural features, and thermal behaviour of these problematic soils will provide a fundamental understanding of their expansive nature and the underlying mechanisms responsible for the volume changes.

The XRD analysis will reveal the dominant presence of swelling clay minerals, such as montmorillonite and vermiculite, and quantify their relative abundance within the soil samples [1, 7, 17 & 27]. This

information will be crucial in understanding the key contributors to the high swelling potential of the expansive soils. The SEM-EDAX investigations will complement the XRD findings by providing insights into the microstructural features and elemental composition of the soils, directly linking the observed morphological characteristics to the presence of specific clay minerals [15, 35 & 40]. The thermal analysis techniques, using TGA and DTA, will shed light on the dehydration and dehydroxylation processes occurring within the clay mineral structure, which are closely associated with the volume change behaviour of the expansive soils [1, 19, 40 & 50].

Based on the insights gained from the comprehensive characterization of the expansive soil samples, the study will explore the effectiveness of a suitable soil stabilization technique in mitigating the challenges associated with these problematic soils. The selected stabilization approach will be assessed for its ability to reduce the swelling potential and enhance the strength characteristics of the soils, offering a sustainable and innovative solution to address the issues encountered in geotechnical engineering projects. The stabilization technique to be evaluated in this study will be chosen based on a thorough review of the existing literature and the specific requirements of the expansive soil samples under investigation. Factors such as long-term durability, environmental sustainability, and cost-effectiveness will be considered in the selection of the stabilization method. The performance of the chosen stabilization technique will be compared with the findings of previous studies, highlighting the novel aspects and potential contributions to the field of geotechnical engineering.

By addressing the objectives of this research, which include the comprehensive characterization of the expansive soil samples and the evaluation of an appropriate stabilization technique, this study aims to provide valuable insights into the fundamental properties and behaviour of these problematic soils. The findings of this study are expected to contribute to the ongoing efforts in the geotechnical engineering community to develop effective and sustainable solutions for the mitigation of the challenges associated with expansive soils, ultimately enabling the successful implementation of construction projects in challenging soil conditions. The comprehensive characterization of the expansive soil samples using advanced analytical techniques, such as XRD, SEM-EDAX, and TGA/DTA, will provide a detailed understanding of their mineralogical composition, microstructural features, and thermal behaviour [29]. This in-depth analysis will shed light on the mechanisms responsible for the swelling and shrinkage phenomena exhibited by the soils, which is crucial for the effective implementation of appropriate stabilization strategies.

Furthermore, the evaluation of a suitable soil stabilization technique, based on the insights gained from the comprehensive characterization, will offer a sustainable and innovative solution to address the challenges associated with expansive soils. The performance of the selected stabilization method in reducing the swelling potential and enhancing the strength characteristics of the soil samples will be thoroughly assessed and compared with the existing stabilization techniques reported in the literature. By combining the comprehensive characterization of the expansive soil samples and the evaluation of an appropriate stabilization technique, this study aims to provide a holistic approach to addressing the issues posed by these problematic soils. The findings of this research are expected to contribute to the

ongoing efforts in the geotechnical engineering community, ultimately enabling the successful implementation of construction projects in challenging expansive soil conditions.

2. Materials and Methods

2.1 Soil Properties

Expansive soils, notorious for their high swelling potential and consequential engineering challenges, were the focus of this study. Detailed analyses were conducted on two types of expansive soils: Soil A, synthesized using sodium bentonite, and Soil B, naturally occurring soil from the suburbs of Chennai, Tamil Nadu, India. The following subsections provide a comprehensive overview of the experimental procedures employed to investigate the properties and behaviour of these soils. Soil A, designed to simulate exceptionally high expanding capability, was prepared using readily available sodium bentonite. Soil B, representing naturally occurring expansive soil, was collected from a location in the suburbs of Chennai. Prior to experimentation, Soil B underwent air-drying at ambient temperature to eliminate moisture and facilitate subsequent processing. The dried soil was then meticulously pulverized using a wooden pestle to break down agglomerated particles and ensure homogeneity.

Distinct grading criteria were established to mimic soils with varying swelling potential. Soil A consisted of soil fractions passing through a 75 μm filter, while Soil B included particles passing through a 1.18 mm sieve. These grading specifications were chosen to replicate real-world scenarios where soil characteristics can vary significantly. To determine the soil index parameters, the experimental procedures followed the relevant Indian standard requirements. Particle size distribution analysis was conducted using a combination of sieve analysis and sedimentation examination, ensuring accurate characterization of the clay content. Compaction characteristics were evaluated through standard proctor compaction tests, providing crucial insights into the soil's behaviour under different compaction efforts. Figures 1(a) and 1(b) present the compaction characteristics of Soil A and Soil B, respectively, illustrating their respective densities as a function of moisture content. Table 1 summarizes the findings of an evaluation of the physical parameters of Soil A and Soil B.

Table 1
Physical properties of the soils used in this study.

Property	Soil A[a]	Soil B[b]
Specific gravity	2.80	2.66
Free swell index (%)	450	105
Liquid limit (%)	276	74
Plastic limit (%)	33	39
Shrinkage limit (%)	8	10
Plasticity index (%)	243	35
Clay (%)	96	72.5
Silt (%)	4	23.5
Sand (%)	-	4
USCS[c] classification	CH	CH
Maximum dry density[d] (g/cm^3)	1.38	1.79
Optimum moisture content[e] (%)	38	19
Mineralogical composition[e] (%)	Montmorillonite: 42–44, Illite: 24–26, Quartz: 14–16, Calcite: 8–10, Feldspar: 2–4	Vermiculite: 46–48, Montmorillonite: 33–34, Quartz: 10–12, Feldspar: 4–6
[a]Commercially obtained sodium bentonite		
[b]Expansive soil obtained from Anna Nagar, Chennai, Tamil Nadu, India		
[c]Unified soil classification system		
[d]Laboratory light compaction tests		
[e]X-ray diffraction		

Both Soil A and Soil B were classified as clay of high plasticity (CH) based on their plasticity characteristics, as per the Unified Soil Classification System (USCS). The Free Swell Index (FSI) values, determined to be 450% for Soil A and 105% for Soil B, indicated their extremely high or substantial expansiveness [41, 43 & 49]. These findings underscore the importance of understanding the swelling potential of expansive soils in engineering applications.

2.2 XRD Analysis

X-ray Diffraction (XRD) is a powerful technique used to analyze the crystallographic structure of materials, making it particularly valuable in the study of soil mineralogy. In this study, XRD analysis was employed to identify and quantify the clay minerals present in the expansive soils, providing insights into their mineralogical composition and potential reactivity. The experimental procedure began with the preparation of soil specimens, which were air-dried to remove moisture and then passed through an ASTM No. 200 standard mesh (75 μm) to isolate the fine clay fraction. Approximately 10 g of the clay fraction, comprising both silt and clay particles, was then mixed with a sodium hexametaphosphate solution to disperse clay particles and prevent aggregation during analysis [7, 22, 42 & 48].

The prepared soil specimens were then subjected to XRD analysis using an X'Pert Pro diffractometer. This instrument emitted X-rays onto the soil specimen at varying angles, causing the X-rays to diffract off the crystal lattice of the soil minerals. By measuring the angle and intensity of the diffracted X-rays, the diffractometer generated a diffraction pattern characteristic of the mineral phases present in the soil sample. The diffraction pattern obtained from XRD analysis was then compared to reference patterns of known minerals to identify the clay mineral constituents present in the soil. Common clay minerals such as kaolinite, illite, and montmorillonite exhibit distinct diffraction peaks at specific angles, enabling their identification and quantification in the soil sample.

2.3 SEM with EDX

Scanning Electron Microscope (SEM) coupled with Energy Dispersive X-ray Analysis (EDX) is a powerful technique used to investigate the morphology, microstructure, and elemental composition of materials at high resolution. In the context of this study, SEM-EDX analysis was employed to examine the surface morphology and elemental composition of expansive soils, providing insights into their structural characteristics and chemical composition [15, 47]. The experimental procedure began with the preparation of soil specimens, following the same protocol as described for XRD analysis. After sample preparation, the soil specimens were mounted onto SEM stubs and gold-coated using the arc discharge method to enhance conductivity and minimize charging effects during imaging.

The prepared soil specimens were then subjected to SEM imaging using an ICON-ESEM QUANTA 200 SEM-EDX system. SEM imaging allowed for high-resolution visualization of the soil microstructure, revealing details such as particle shape, size, and surface features. EDX analysis, on the other hand, enabled the identification and quantification of elemental constituents present in the soil matrix. By analyzing the elemental composition of the soil samples, EDX provided valuable information about the distribution and abundance of key elements such as silicon, aluminum, iron, and calcium, which are indicative of clay minerals and other soil constituents. Additionally, SEM imaging facilitated the observation of microstructural features such as grain boundaries, pore structure, and particle aggregation, offering insights into the physical properties and behaviour of the expansive soils.

2.4 TGA and DTA Analysis

Thermogravimetry (TGA) and Differential Thermal Analysis (DTA) are complementary techniques used to analyze the thermal behaviour and decomposition kinetics of materials. In the context of this study, TGA-DTA analysis was employed to investigate the thermal stability and presence of energetic clay minerals within the expansive soils, providing insights into their thermal properties and potential reactivity. The experimental procedure began with the preparation of soil specimens, following the same protocol as described for XRD and SEM-EDX analyses. After sample preparation, the soil specimens were subjected to TGA-DTA analysis using an automatic STA 6000 thermal analyzer, operating under static air conditions with a controlled heating rate [13].

During TGA analysis, the weight of the soil specimen was continuously monitored as a function of temperature or time, allowing for the detection of mass loss due to decomposition, dehydration, or other thermal events. DTA, on the other hand, measured the temperature differential between the soil specimen and an inert reference material, providing information about exothermic or endothermic reactions occurring within the sample. By analyzing the thermal behaviour of the expansive soils, TGA-DTA provided valuable insights into their decomposition kinetics, thermal stability, and presence of clay minerals with high thermal reactivity. The detection of mass loss events and thermal transitions enabled the identification of clay mineral dehydration, organic matter decomposition, and other thermal phenomena occurring within the soil matrix.

2.5 FTIR Analysis

Fourier-Transform Infrared Spectroscopy (FTIR) is a versatile technique used to analyze the chemical composition and molecular structure of materials based on their infrared absorption spectra. In the context of this study, FTIR analysis was employed to identify chemical interactions and functional groups present in the expansive soils, providing insights into their chemical composition and bonding characteristics. The experimental procedure began with the preparation of soil specimens, following the same protocol as described for XRD, SEM-EDX, and TGA-DTA analyses. After sample preparation, the soil specimens were subjected to FTIR analysis using a NICOLET 6700FT-IR spectrometer, which emitted infrared radiation onto the soil sample and measured the absorbance of infrared light at different wavelengths [10].

By analysing the FTIR spectra of the expansive soils, valuable information about the organic functional groups and mineral constituents present in the soil matrix was obtained. Peaks in the FTIR spectra corresponded to specific chemical bonds and molecular vibrations associated with clay minerals, organic matter, and other soil constituents, allowing for their identification and quantification. FTIR analysis enabled the detection of functional groups such as hydroxyl (OH), carbonyl (C = O), and silicate (Si-O) groups, which are characteristic of clay minerals and organic matter present in the expansive soils. By correlating the FTIR spectra with reference spectra of known compounds, valuable insights were gained into the chemical composition and bonding characteristics of the soil samples.

3. Results and Discussions

XRD, SEM with EDX, TGA, DTA, and FTIR experiments were conducted in order to better comprehend the nature clay, as stated in the following sections.

3.1 XRD characterization

The X-ray diffraction (XRD) pattern in Fig. 2 serves as a critical tool for elucidating the crystalline mineral phases inherent within the expansive soil samples. Through the careful examination of this pattern, researchers can glean valuable insights into the intricate atomic arrangements and concentrations of various crystalline minerals present. Notably, distinct peaks in the XRD pattern correspond to specific atomic spacings and intensities, reflecting the abundance of key minerals such as smectite clays (including the highly expansive montmorillonite), kaolinite, illite, and quartz [7, 22 & 49].

Analysis of the XRD pattern holds significant importance in discerning the mineralogical composition of expansive soils, a fundamental aspect directly influencing their swelling and shrinkage behaviour. By identifying and quantifying the presence of different minerals, researchers can better comprehend the underlying mechanisms driving soil expansion and contraction phenomena [19, 27, 40 & 50]. For instance, the predominance of smectite clays like montmorillonite typically correlates with heightened swelling potential, owing to their unique interlayer structures capable of accommodating water molecules.

Furthermore, the XRD analysis facilitates the characterization of soil samples based on their mineralogical profiles, providing valuable data for predictive modelling and engineering applications. Understanding the mineralogical composition empowers researchers to tailor soil stabilization strategies, effectively mitigating detrimental effects such as swelling-induced damage to infrastructure.

3.2 SEM with EDX characterization

The scanning electron microscope (SEM) images presented in Figs. 3a and 3b provide intricate insights into the microstructural attributes and particle morphology of the expansive soil samples under investigation. Notably, the SEM image of Soil A (Fig. 3a) unveils a dispersed and flocculated arrangement of soil particles characterized by irregular and platey shapes. In contrast, the SEM image of Soil B (Fig. 3b) showcases a more compact and oriented microstructure adorned with uniform and elongated particles [15, 40 & 47]. These distinct morphological features are indicative of variations in the mineralogical composition and physico-chemical properties of the two soil samples.

The observed differences in particle morphology and packing are intricately linked to the engineering behaviour of expansive soils, encompassing critical parameters such as swelling potential, hydraulic conductivity, and shear strength. Soil A's dispersed arrangement, coupled with irregular platey shapes, suggests a potentially higher swelling propensity owing to increased surface area and interparticle spaces. Conversely, Soil B's more compact microstructure, characterized by uniform and elongated particles, may exhibit enhanced stability and reduced swelling tendencies, attributed to tighter particle packing and lesser interstitial voids.

Further insights into the elemental composition of Soil A and Soil B are gleaned through energy dispersive X-ray (EDX) analysis, as depicted in Figs. 4a and 4b. The EDX spectra furnish quantitative data regarding the relative abundance of major elements (e.g., Si, Al, Fe, Ca, Mg, Na, K) and minor elements (e.g., Ti, Co) present in the soil samples. Discrepancies in the elemental composition between the two soil samples underscore variations in their mineralogical makeup, crucial for elucidating the engineering properties and behaviour of expansive soils [47].

The elemental composition data, meticulously tabulated in Table 2, further corroborate the nuanced differences in the geochemical characteristics of Soil A and Soil B. These quantitative insights, obtained through EDX analysis, serve as foundational pillars for developing a comprehensive understanding of the expansive soils' geochemical attributes, guiding effective soil management and stabilization strategies.

Table 2
Elemental composition of expansive soils using EDX.

Soil A		**Soil B**	
Element	**Weight (%)**	**Element**	**Weight (%)**
C: Carbon	7.31	C: Carbon	8.96
O: Oxygen	47.26	O: Oxygen	49.22
Na: Sodium	1.46	Na: Sodium	2.39
M: Magnesium	1.38	Mg: Magnesium	1.37
Al: Aluminium	12.49	Al: Aluminium	9.20
Si: Silicon	21.15	Si: Silicon	22.73
K: Potassium	0.93	K: Potassium	3.16
C: Calcium	2.62	Fe: Iron	2.87
Ti: Titanium	0.47	Co: Cobalt	0.10
Fe: Iron	4.94	-	

In addition to SEM and EDX analyses, the examination of SEM images at 5000 resolution and the execution of EDX examinations at specific operating parameters (25 kV voltage, 10 mm operating distance, 52 spot size) provide detailed microstructural and elemental information critical for comprehensive soil characterization. By synergistically integrating SEM, EDX, and elemental composition data, a holistic picture of the expansive soils' properties and behaviour emerges, facilitating informed decision-making in various engineering and environmental applications.

3.3 TGA and DTA characterization

The thermogravimetric analysis (TGA) and differential thermal analysis (DTA) represent indispensable techniques for elucidating the thermal properties and phase transitions of expansive soil specimens,

offering profound insights into their behaviour across a range of temperature conditions.

As illustrated in Fig. 5a, the TGA curve for Soil A delineates a distinctive pattern of mass loss commencing around 660°C and extending up to 840°C. This significant mass reduction corresponds to the dehydration and subsequent dehydroxylation phenomena inherent to the clay minerals present within Soil A. Concurrently, the DTA curve exhibits discernible endothermic shifts, indicative of the energy absorption associated with these thermal transformations [13].

In Fig. 5b, the TGA and DTA contours for Soil B manifest pronounced thermal characteristics, distinct from those observed in Soil A. Soil B undergoes an initial phase of rapid weight loss between 60°C and 120°C, attributable to moisture evaporation, followed by a linear weight reduction attributed to dehydroxylation, persisting up to 660°C [13]. These thermal behaviours are intricately linked to the mineralogical composition of Soil B, notably characterized by the presence of montmorillonite, as corroborated by the resemblance to endothermic peaks observed in unprocessed montmorillonite.

The acquired thermal analysis data afford unparalleled insights into the specific clay minerals and mineral phases constituting the expansive soil samples. This detailed understanding is paramount for assessing the soils' propensity for swelling and shrinkage, as well as their thermal stability and reactivity across varying temperature regimes.

3.4 FTIR characterization

The Fourier transform infrared (FTIR) spectroscopy analysis, depicted in Fig. 6, serves as a pivotal tool for unravelling the molecular structure and functional groups present within expansive soil matrices. By virtue of its ability to detect the characteristic absorption bands corresponding to specific chemical bonds and functional groups, FTIR spectroscopy offers invaluable insights into the organic and inorganic constituents of the soil samples [10, 19 & 27].

The FTIR spectrum, spanning from 500 cm^{-1} to 4500 cm^{-1} for Soil A and Soil B, respectively, as depicted in Figs. 6 (a) and 6 (b), unveils a rich tapestry of absorption bands indicative of diverse molecular interactions within the soil matrices. These absorption bands, arising from stretching and bending vibrations of various functional groups, including O-H, Si-O-Si, Al-O-Si, C-H, and C = O, provide a fingerprint of the chemical composition and structural arrangement of the soil constituents [40].

In Soil A, the FTIR spectrum showcases prominent absorption bands at 825 cm^{-1} (medium), 1632 cm^{-1} (strong), and 3700 cm^{-1} (weak), corresponding to characteristic vibrations associated with smectite clay minerals such as montmorillonite. These bands signify the presence of hydroxyl (OH) groups, likely originating from minerals like kaolinite, as well as water (H2O) molecules absorbed within the soil matrix [10, 40].

Similarly, the FTIR spectrum of Soil B exhibits distinct absorption bands at 720 cm^-1 (medium), 1697 cm^{-1} (weak), 3088 cm^{-1} (weak), and 3830 cm^{-1} (medium), indicative of montmorillonite clay particles with associated hydroxyl (OH) groups and water (H_2O) molecules. These bands corroborate the

presence of montmorillonite within Soil B, underscoring its mineralogical composition and providing insights into its molecular structure.

4. Sustainable solutions for stabilization of expansive soils

4.1 Physical/Mechanical stabilization

4.1.1 Reinforcement with Geogrids

Expansive soils, as characterized in the study, exhibit high plasticity and substantial expansiveness, which can lead to significant swelling and shrinkage. The XRD analysis revealed the presence of minerals such as smectite clays (including montmorillonite) and kaolinite, known for their expansive behaviour. Geogrids offer mechanical reinforcement to mitigate these effects by improving the soil's tensile strength and reducing lateral deformation. SEM-EDX characterization provided insights into the microstructural attributes of the soil samples, indicating variations in particle morphology and packing. Soil A, with its dispersed arrangement of irregular particles, may benefit from geogrid reinforcement to enhance stability and reduce the potential for excessive swelling. Conversely, Soil B was more compact microstructure suggests a need for reinforcement to minimize lateral movement and maintain stability over time.

When evaluating geogrids for engineering applications, it's crucial to assess both their microstructural characteristics and physical properties as shown in Table 3. Microstructural analysis involves examining aspects such as the size and shape of apertures, the arrangement of ribs, and the material composition of the geogrid. These factors influence how well the geogrid interacts with the soil, providing stability, reinforcement, and drainage as needed [51]. Physical property analysis delves into the geogrid's mechanical behaviour, including its tensile strength, flexural rigidity, puncture resistance, interface friction, and water permeability. These properties determine the geogrid's ability to withstand loading conditions, resist damage, and maintain stability over time. By carefully considering both microstructural characteristics and physical properties, engineers can select geogrids that offer optimal performance and durability for specific geotechnical applications, ultimately ensuring the long-term success of infrastructure projects [16]. By incorporating geogrids into the soil structure, it's possible to restrain the lateral expansion of the soil particles, thereby mitigating the effects of swelling and shrinkage. This reinforcement mechanism, coupled with appropriate soil improvement techniques, can help stabilize the soil mass and enhance its engineering properties.

Table 3
Comprehensive analysis of geogrid specifications on expansive soils.

Properties	Description	Advantage	Key Considerations	Reference
Microstructure Analysis				
Aperture Size and Shape	Evaluation of Aperture Geometry	Enhanced Soil Confinement	Hexagonal, Rectangular, and Triangular Shapes	[51]
Rib Configuration	Analysis of Rib Arrangement	Improved Load Distribution	Staggered or Integral Ribs Offering Multidirectional Reinforcement	[51]
Material Composition	Assessment of Geogrid Constituents	Durable and Compatible with Soil	High-Density Polyethylene (HDPE), Polyester, Polypropylene	[16, 58]
Physical Property Analysis				
Tensile Strength	Ultimate Strength and Deformation Behaviour	Essential for Structural Integrity	Sufficient Strength to Resist Loads and Soil Conditions	[52, 58]
Flexural Rigidity	Rigidity and Load Distribution	Ensures Stability under Various Loads	High Flexural Rigidity to Minimize Deformation and Enhance Stability	[58]
Puncture Resistance	Resistance to Penetration and Damage	Prevents Structural Failure	Enhanced Resistance to Maintain Long-Term Performance and Prevent Soil Intrusion	[58]
Interface Friction	Interaction with Surrounding Soil	Enhances Soil-Retaining Ability	Superior Interface Friction for Greater Stability and Resistance to Soil Movement	[32]
Water Permeability	Drainage Efficiency and Soil Consolidation	Facilitates Efficient Drainage and Stability	Enhanced Permeability to Reduce Saturation-Induced Instability and Improve Soil Performance	[57]

4.1.2 Geotextile Encapsulation

Geotextiles act as a barrier to control moisture infiltration and minimize volume changes in expansive soils. The FTIR analysis provided insights into the molecular structure and functional groups present within the soil matrices, highlighting the presence of hydroxyl (OH) groups and water (H_2O) molecules. These findings underscore the importance of managing moisture ingress to control swelling and shrinkage. By encapsulating the expansive soil with geotextiles, it's possible to create a barrier that limits the penetration of water and reduces the risk of volume changes. This approach can help maintain soil stability and prevent adverse effects on nearby structures or infrastructure. Additionally, SEM images revealed the microstructural attributes of the soil samples, indicating variations in particle morphology.

Geotextile encapsulation can help stabilize the soil particles and prevent excessive movement, particularly in areas prone to high moisture levels or fluctuating environmental conditions.

When encapsulating expansive soil, the challenge faced for selecting geotextiles that effectively mitigate soil expansion, moisture fluctuations, and erosion. Beyond basic characteristics, several crucial considerations come into play as shown in Table 4. Firstly, geotextiles must be compatible with the unique properties of expansive soil, including its expansive behaviour and plasticity, to ensure effective stabilization and reinforcement. Additionally, durability and longevity are paramount, as expansive soil environments subject geotextiles to significant stress over time. Factors such as UV resistance, chemical stability, and resistance to biological degradation are crucial to withstand these conditions [20, 45].

Table 4
Geotextile encapsulation methods on expansive soils.

Geotextile Type	Recommended Use	Advantages	References
Woven Geotextiles	Used for stabilization and reinforcement in expansive soil Applications: especially under heavy loads.	- High tensile strength for restraining soil expansion	[20]
		- Excellent load distribution properties to minimize surface deformation	[36]
		- Provides long-term stability and reinforcement in expansive soil conditions	[20]
Non-Woven Geotextiles	Ideal for filtration and separation functions in expansive Applications: particularly for drainage improvement.	- Offers excellent permeability for effective drainage	[45, 60]
		- Prevents soil particles from migrating while allowing water to flow through	[45, 60]
		- Enhances soil stabilization by reducing erosion and promoting consolidation	[60]
High-Performance Geotextiles	Suitable for reinforcement and erosion control in expansive soil Applications: offering enhanced resistance to deformation and erosion.	- Provides superior strength and durability for long-term performance	[53]
		- Ensures stability and integrity in high-stress environments	[53, 55]
		- Reduces maintenance requirements and prolongs the service life of structures	[55]

Installation considerations are also vital, as geotextiles should integrate seamlessly with construction methods and existing structures. Whether through direct placement, trenching, or backfilling, ease of

handling and installation is essential. Furthermore, environmental impact should be minimized, with sustainable options favoured to reduce ecological footprints. Cost-effectiveness is another critical factor. One must balance performance and durability with initial material costs, installation expenses, and long-term maintenance requirements. By considering these factors alongside basic characteristics, such as tensile strength and permeability, selecting geotextiles that effectively encapsulate expansive soil while meeting project objectives in a sustainable, cost-effective manner.

4.2 Chemical Stabilization

Soil improvement techniques, such as lime or cement stabilization, offer a means to modify the soil's properties and reduce its susceptibility to volume changes. The TGA-DTA analysis provided insights into the thermal behaviour of the soil specimens, highlighting the presence of clay minerals with high thermal reactivity. By combining soil improvement techniques with geosynthetics, it's possible to create composite systems that leverage the strengths of both materials. For example, cement-treated soil reinforced with geogrids can offer enhanced stability and durability, particularly in areas with high traffic loads or dynamic loading conditions. The elemental composition data obtained through SEM-EDX analysis further corroborate the nuanced differences in the geochemical characteristics of the soil samples. This information can guide the selection of appropriate soil improvement additives and stabilization methods tailored to the specific mineralogical makeup of the expansive soils.

The selection between lime and cement stabilization techniques for managing expansive soil is critical. Lime stabilization involves altering the soil's chemical properties to reduce plasticity and curb swelling tendencies. Conversely, cement stabilization entails introducing cementitious compounds into the soil, enhancing its strength and resilience. This decision hinges on a thorough evaluation of soil composition, project specifications, and desired outcomes as shown in Table 5. By conducting detailed analyses of microstructural features and physical properties, including mineralogical composition, compaction characteristics, and compressive strength, stakeholders can make informed decisions tailored to the unique challenges posed by expansive soil. Such a technical assessment aids in selecting the most suitable stabilization method, ensuring effective and sustainable management of expansive soil conditions [31, 33].

Table 5
Comparative assessment of lime and cement stabilization on Expansive Soils.

Aspect	Lime stabilization	Cement stabilization	References
Microstructural Analysis			
XRD (X-Ray Diffraction)	Presence of expansive clay minerals suggests suitability for lime stabilization	Presence of expansive clay minerals may indicate potential for cement stabilization	[12, 59]
FTIR (Fourier Transform Infrared Spectroscopy)	Organic content and potential presence of cementitious materials favour lime stabilization	Organic content and potential presence of cementitious materials may favour cement stabilization	[30]
TGA/DGA (Thermogravimetric Analysis/Differential Gravimetric Analysis)	Lime stabilization can mitigate organic content and promote pozzolanic reactions	Cement stabilization can mitigate organic content and promote pozzolanic reactions	[12]
SEM-EDX (Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy)	Suitable soil fabric and presence of cementitious compounds may favour lime stabilization	Presence of cementitious compounds in soil may favour cement stabilization	[12, 30, 59]
Physical Property Analysis			
Compaction Characteristics	Lime can improve workability and compaction properties	Cement can enhance soil density and stability	[31, 33]
Unconfined Compressive Strength (UCS)	Lime stabilization can increase UCS and reduce soil plasticity	Cement stabilization can significantly increase UCS	[3, 6 & 26]
Hydraulic Conductivity	Lime can improve drainage and reduce soil moisture content	Cement can decrease hydraulic conductivity and limit swelling potential	[23, 33]
pH and Alkalinity	Lime can raise soil pH and reduce alkalinity	Cement may have minimal impact on soil pH and alkalinity	[33]

4.3 Biological Stabilization

Biological stabilization methods offer innovative and sustainable solutions for managing expansive soils, leveraging natural processes to enhance soil properties as shown in Table 6. One prominent technique is Microbial-Induced Calcite Precipitation (MICP), which uses urease-producing bacteria such as Sporosarcina pasteurii to hydrolyse urea, resulting in the precipitation of calcium carbonate (calcite) within the soil matrix. This process significantly reduces soil permeability and plasticity while increasing compressive strength and overall stability, making it effective for mitigating the swelling behaviour of

expansive soils. Enzyme-Induced Calcite Precipitation (EICP) is a similar approach that employs enzymes like urease to catalyse the formation of calcium carbonate, enhancing soil compaction and load-bearing capacity. This method improves soil structure by forming strong bonds between particles, which is crucial for reducing the deformation potential of expansive soils under varying moisture conditions [28].

Table 6
Biological stabilization methods on expansive soils.

Treatment Method	Description	Soil Benefits	Durability	References
Microbial-Induced Calcite Precipitation (MICP)	Utilizes bacteria to precipitate calcium carbonate in the soil	- Reduces soil permeability and plasticity - Increases soil strength and stability	- Long-term durability due to stable calcium carbonate formation	[28]
Enzyme-Induced Calcite Precipitation (EICP)	Uses enzymes to accelerate calcium carbonate precipitation in soil	- Enhances soil compaction and load-bearing capacity - Improves soil structure	- Medium to long-term durability with proper application and curing	[25]
Plant Root Reinforcement	Involves planting vegetation with deep root systems	- Enhances soil cohesion and reduces erosion - Improves soil organic content and structure	- Varies depending on plant type and maintenance; generally long-term with perennial plants	[54]
Biochar Amendment	Adds biochar to soil to improve its properties	- Enhances soil fertility and water retention - Reduces soil swelling and shrinkage	- Long-term durability as biochar remains stable in soil for years	[56]
Biopolymer Treatment	Utilizes natural polymers (e.g., xanthan gum, guar gum) to bind soil particles	- Increases soil cohesion and strength - Reduces soil erosion and dust formation	- Medium to long-term durability depending on environmental conditions and biopolymer type	[9, 34]

Plant root reinforcement is another biological method, involving the use of deep-rooted vegetation such as vetiver grass or certain tree species. These plants develop extensive root systems that bind soil particles, increase cohesion, and reduce erosion. The organic matter contributed by decaying roots also

improves soil structure and fertility over time, which is beneficial for the long-term stabilization of expansive soils. Biochar amendment involves incorporating biochar, a stable form of carbon-rich charcoal produced from organic material, into the soil. Biochar's high porosity and surface area enhance soil water retention and nutrient availability while reducing swelling and shrinkage. Its stability in the soil ensures long-term benefits, making it an effective amendment for improving the physical properties of expansive soils [46].

Biopolymer treatment utilizes natural polymers, such as xanthan gum or guar gum, to bind soil particles together. These biopolymers increase soil cohesion and strength, reducing erosion and dust formation. Biopolymer treatment offers a sustainable and effective method for stabilizing expansive soils, with the durability of the treatment depending on environmental conditions and the specific biopolymer used [34]. Each of these biological stabilization methods provides unique advantages for managing expansive soils, offering sustainable and long-lasting improvements in soil properties. By carefully analyzing soil conditions and project requirements, the most suitable biological stabilization technique can be selected to achieve optimal soil stability and performance [9].

The utilization of biopolymers presents an eco-friendly and sustainable approach to soil improvement techniques for stabilizing expansive soils. The FTIR analysis provided valuable insights into the molecular structure and functional groups present within the soil matrices, indicating the presence of organic matter and potential interactions with biopolymers. By incorporating biopolymers into the soil matrix, it is possible to modify the soil's physico-chemical properties and enhance its resistance to volume changes. The addition of biopolymers can contribute to the formation of stable soil aggregates, improving soil structure and reducing the potential for swelling and shrinkage. The microstructural information obtained through SEM analysis can guide the selection of appropriate biopolymer types and application methods. The observed variations in particle morphology and packing may influence the interaction between the biopolymers and soil particles, affecting the overall stabilization efficacy. Furthermore, the elemental composition data from SEM-EDX analysis can provide insights into the potential chemical interactions between the biopolymers and the soil constituents. This information can facilitate the optimization of biopolymer formulations tailored to the specific geochemical characteristics of the expansive soil samples, ensuring effective stabilization and long-term durability.

4.4 Composite Systems

Composite systems, combining geosynthetics (geofoam) with other stabilization methods, offer synergistic benefits that enhance the overall performance and durability of the soil structure. The XRD analysis revealed the mineralogical composition of the soil samples, providing insights into the dominant clay minerals present. By integrating geosynthetics with soil improvement techniques, it's possible to create composite systems that address multiple factors contributing to soil instability. For example, combining geogrid reinforcement with lime stabilization can improve soil strength and reduce swelling potential, offering a holistic solution to the challenges posed by expansive soils.

The SEM images and EDX analysis provided detailed microstructural and elemental information critical for comprehensive soil characterization. This data can inform the design and implementation of composite systems tailored to the specific engineering requirements and environmental conditions of the project site.

5. Conclusions

The comprehensive characterization of expansive soils through a suite of advanced analytical techniques (XRD, SEM-EDX, TGA, DTA, and FTIR) and mechanical tests has provided a holistic understanding of their microstructural attributes and mechanical behaviour. These findings serve as a robust foundation for selecting appropriate stabilization techniques tailored to the specific characteristics of the expansive soil samples investigated in this study.

XRD analysis identified the presence of swelling clay minerals like smectite (including montmorillonite), which are primarily responsible for the expansive nature of the soils. SEM-EDX revealed variations in particle morphology, packing arrangements, and elemental composition between the soil samples, necessitating tailored stabilization approaches. TGA and DTA elucidated the thermal behaviour, dehydration, and dehydroxylation processes, indicating the presence of reactive clay minerals and guiding stabilization technique selection based on temperature conditions. FTIR provided insights into the molecular structure and organic/inorganic constituents within the soil matrices. Mechanical tests evaluated critical properties like strength, compressibility, and volume change characteristics, directly linked to the engineering performance of the expansive soils.

By integrating these comprehensive microstructural and mechanical findings, an informed selection of stabilization techniques can be made. Potential solutions include reinforcement with geogrids for soils with dispersed particle arrangements to enhance stability and reduce swelling, geotextile encapsulation as a moisture barrier to control volume changes, chemical stabilization using lime or cement to modify soil properties, biopolymer stabilization and composite systems combining geosynthetics with other stabilization methods for synergistic benefits.

This holistic approach, considering both microstructural attributes and mechanical behaviour, enables the development of tailored stabilization strategies that effectively mitigate the detrimental effects of expansive soils on infrastructure. The findings underscore the importance of leveraging advanced characterization techniques to gain a comprehensive understanding of problematic soils and select appropriate stabilization solutions, ultimately ensuring long-term stability and durability of construction projects in challenging soil conditions

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Conflicts of interest/Competing interests

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

Availability of Data and Material:

The data that guide the results of this research will be available openly.

Code availability:

Not applicable

Author contributions:

SS conceptualized the presented idea, derived the methodology, designed and performed the experiments and writing original draft. BS developed the theory, supervised the findings, supported in writing review and editing. NR article drafting and contributed to the final version of the manuscript. PK supported in article drafting, reviewing and editing.

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Figures

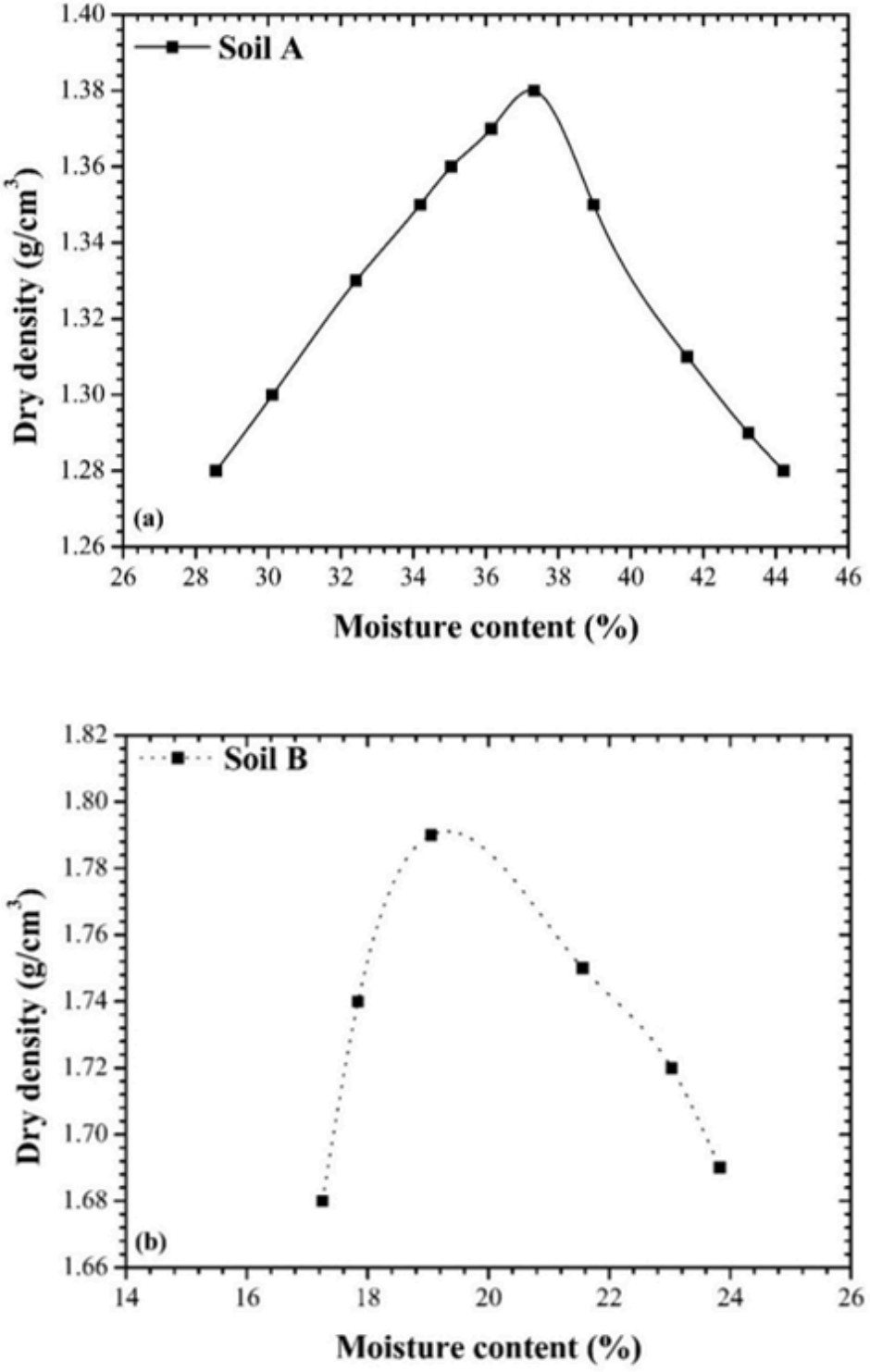

Figure 1

Compaction characteristics of (a) Soil A and (b) Soil B

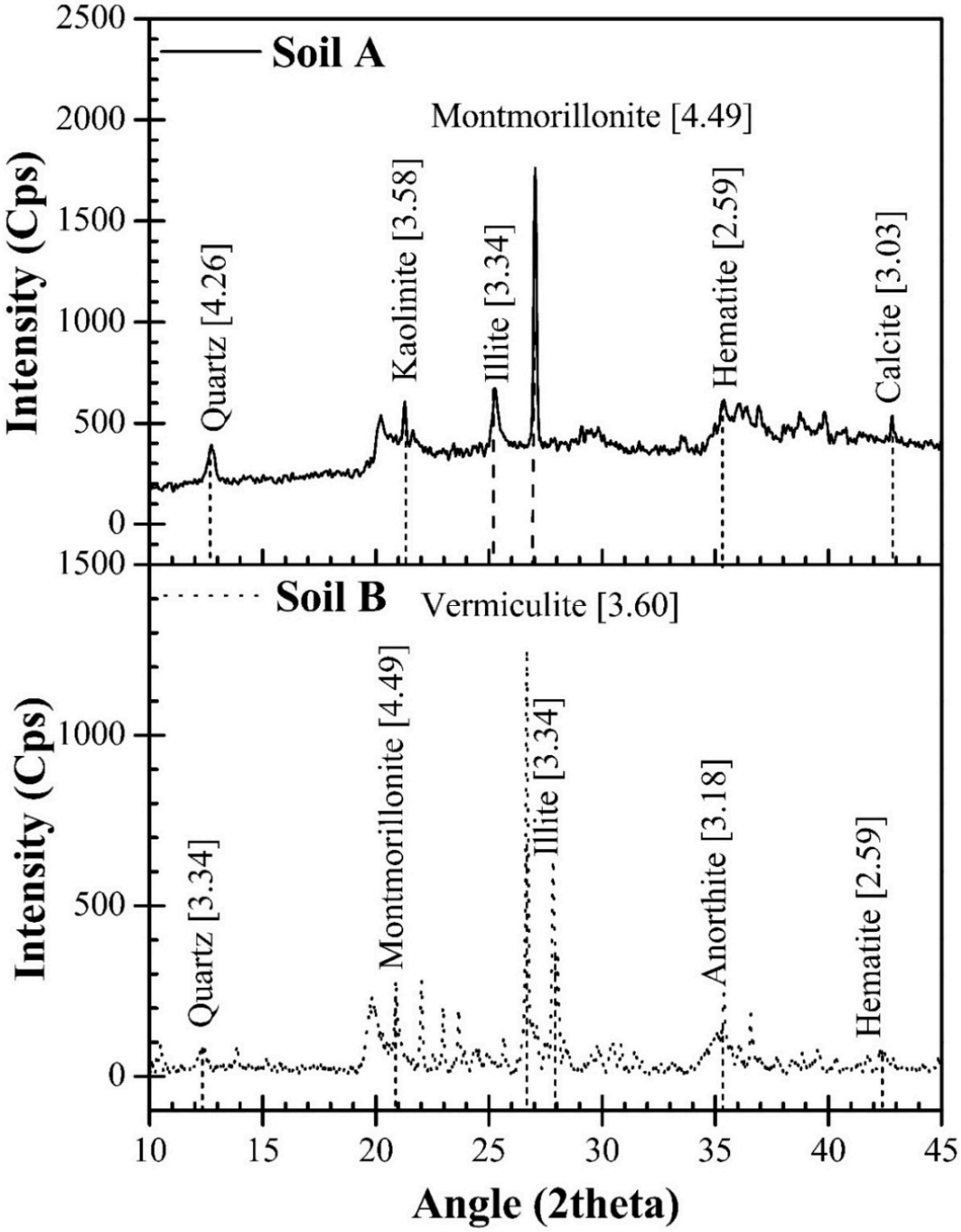

Figure 2

X-Ray diffraction pattern of expansive soils

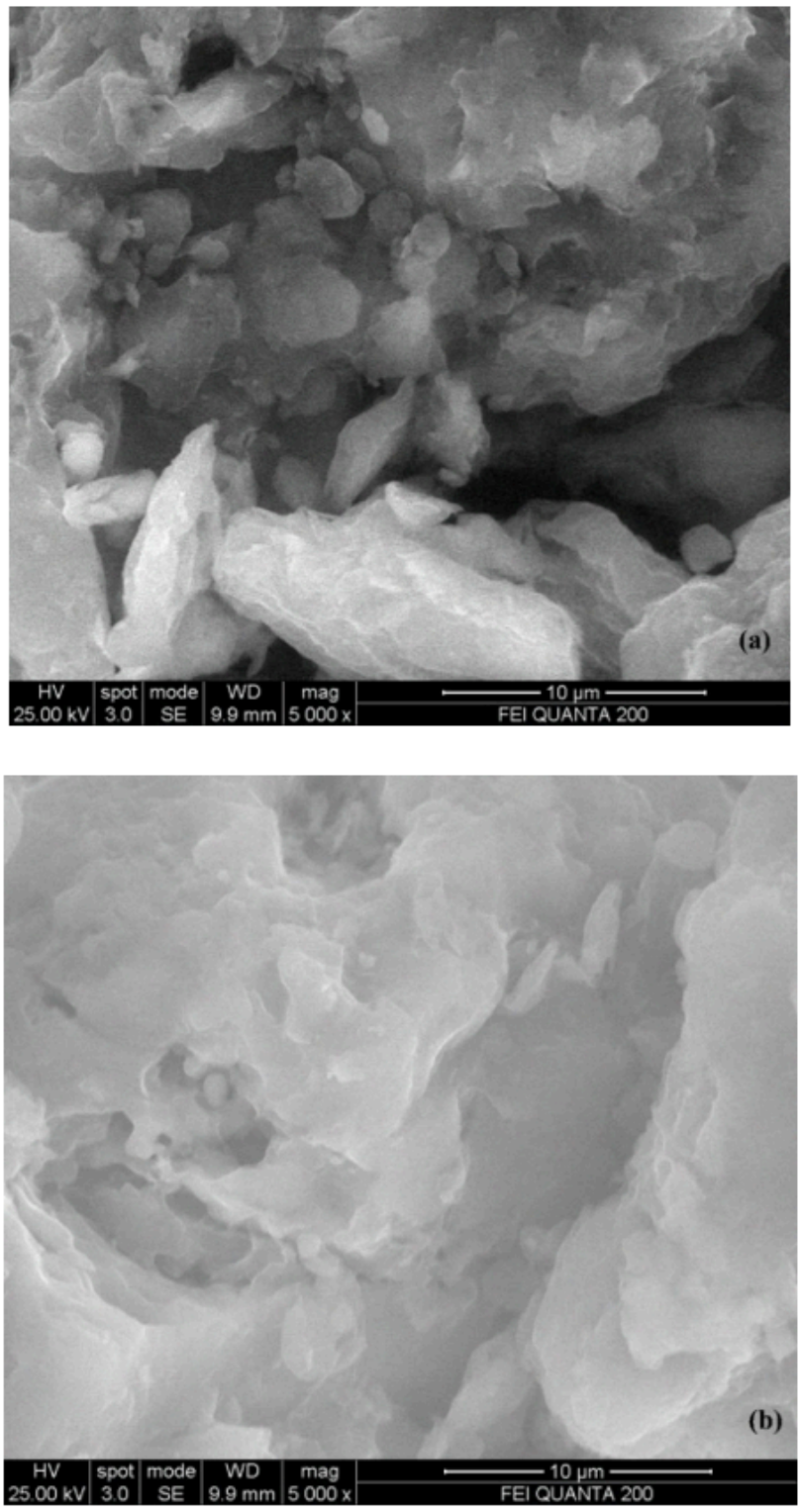

Figure 3

Scanning electron microscope images of (a) Soil A and (b) Soil B

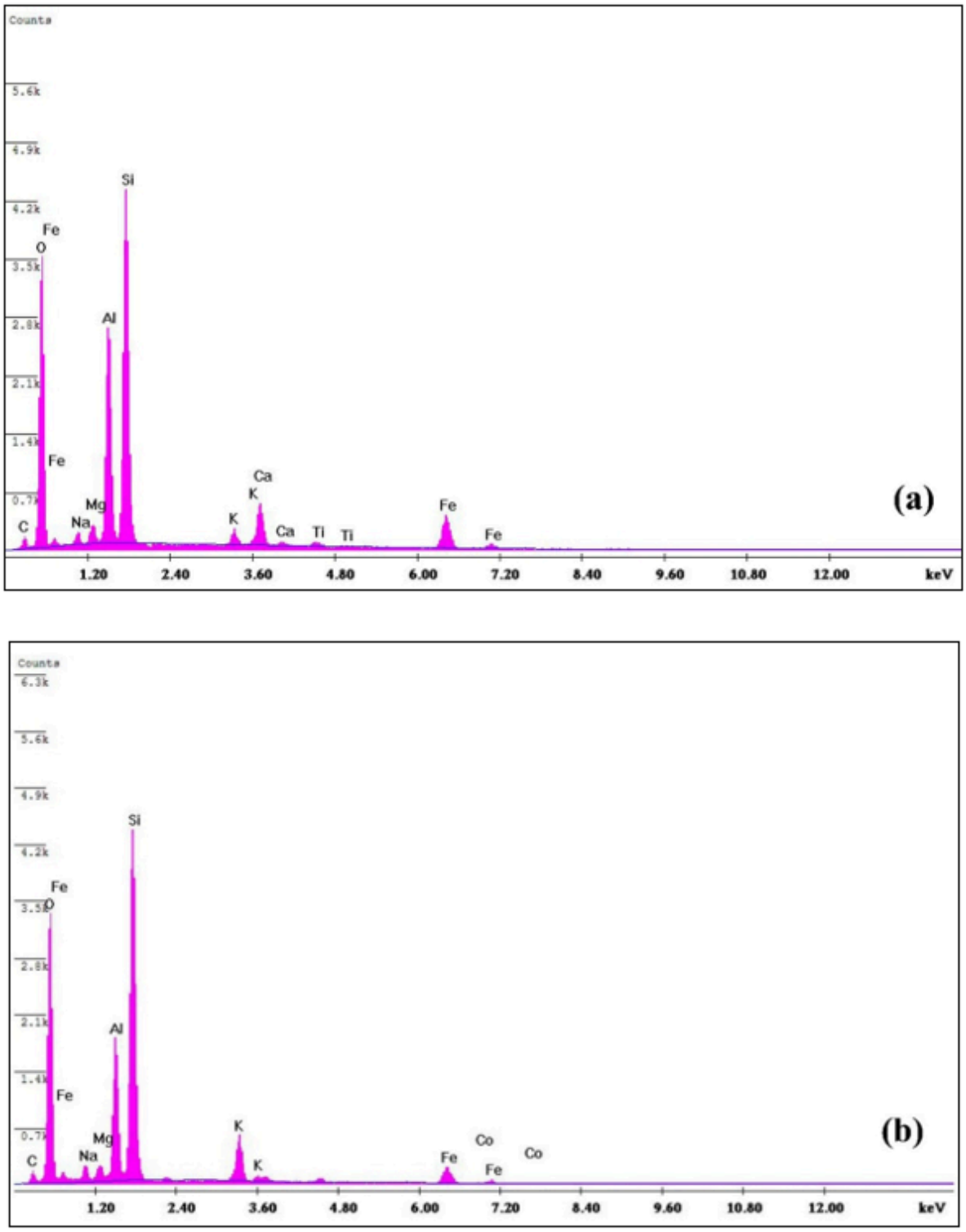

Figure 4

Energy dispersive X-Ray analysis spectrum of (a) Soil A and (b) Soil B

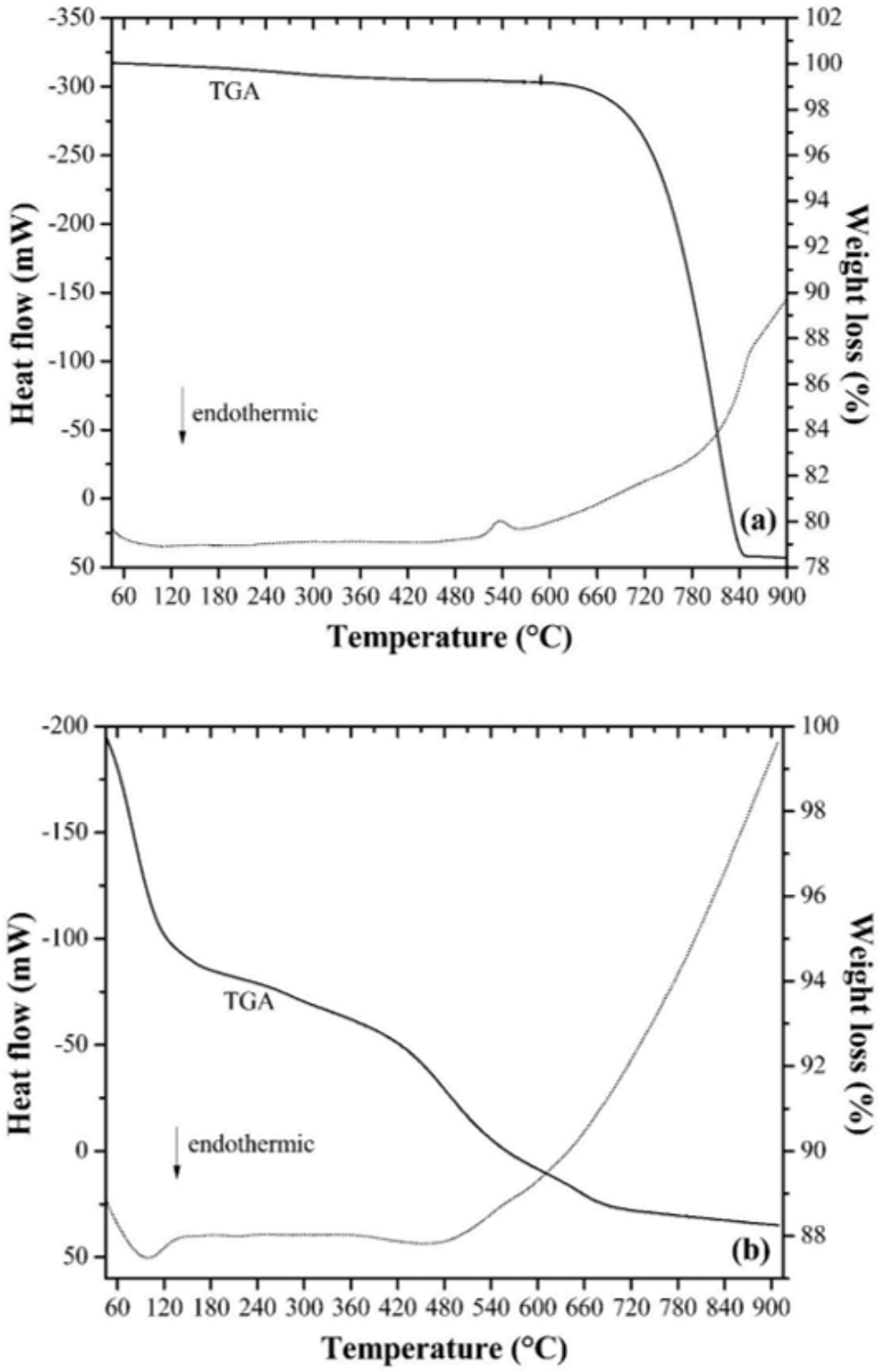

Figure 5

TGA and DTA curve of (a) Soil A and (b) Soil B

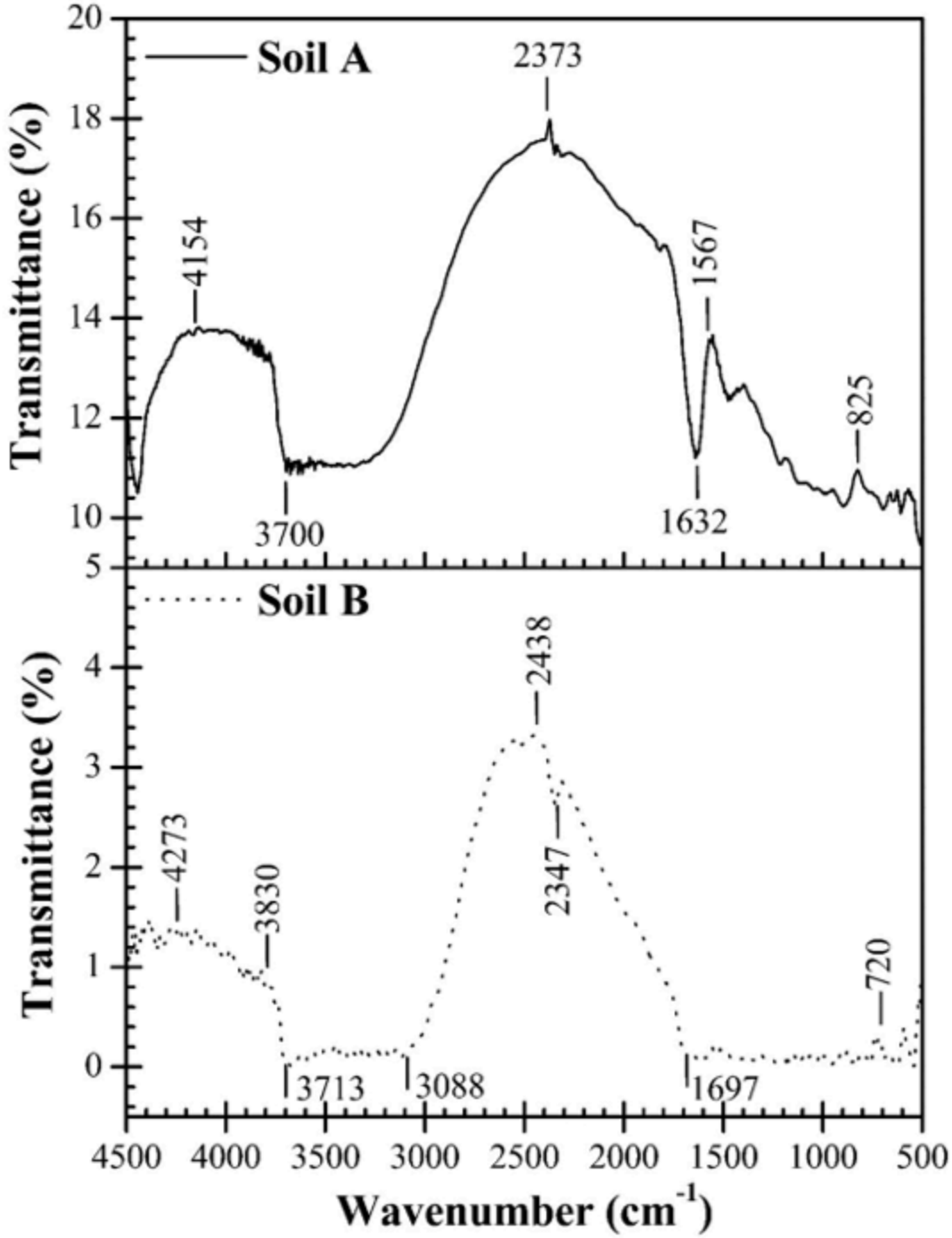

Figure 6

FTIR pattern of expansive soils