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Reassessment of natural expansive materials and their impact on freeze-thaw cycles in geotechnical engineering: a review

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The stabilization and application of expansive geomaterials are critical in geotechnical engineering. These naturally expansive materials exhibit complex hydro-chemo-mechanical properties because they undergo volumetric changes in response to variations in moisture content and/or temperature. The characteristic shrink-swell behavior of these materials makes their use problematic and plays a substantial role in influencing the stability of geo-infrastructure applications. However, there is a lack of comprehensive knowledge of the mechanisms and factors impacting their behavior to ensure mechanical integrity in natural and built infrastructure and geo-engineering projects. This work provides a comprehensive review of the intrinsic and extrinsic factors contributing to the shrink-swell behavior and expansion mechanisms of frost-heaving and natural-expansive geomaterials, such as expansive clays and sulfate minerals. We reviewed and synthesized peer-reviewed published works in various databases and academic repositories in the last 100 years. The influence of shrink-swell behavior of these geomaterials and the critical role they play in engineering infrastructure were highlighted, explicitly focusing on their involvement in geotechnical-related hazards, such as the freeze-thaw cycle, and the damage and sulfate-attack of geo-infrastructure. We analyzed the interactions between clay minerals, especially how bentonite enhances grout stability and acts as a buffer material in high-level nuclear waste repositories. The findings indicate that water interaction with geomaterials and concrete can cause about a 10% volume expansion when frozen. Also, the exposure of fractured rocks to low ($\leq 0^{\circ}\text{C}$) and high ($> 0^{\circ}\text{C}$) temperatures can greatly change rock deformation and strength. Finally, gypsum interacting with water can theoretically increase in volume by 62% to form ice crystals. This forward-leading review presents the advantages, disadvantages, and unresolved issues of expansive natural geotechnical materials that improve the resiliency and sustainability of geological infrastructure.

KEYWORDS

geomaterials, expansive clay, frost-heaving, sulfate minerals, soil improvement, geotechnical engineering

1 Introduction

Natural expansive geomaterials are essential to geotechnical engineering due to their unique properties during the construction and reinforcement of surface, near-surface, and underground infrastructure. These natural expansive materials exhibit complex hydro-chemo-mechanical properties, and their use poses a threat because they undergo volumetric changes in response to variations in moisture content and/or temperature.

These geomaterials often exhibit a freeze-thaw behavior, and their expansion and shrinkage mechanism can be detrimental to geo-infrastructure. Geo-infrastructure refers to infrastructures built on or around geomaterials (rocks and soils) on the surface, near-surface, and deep underground environments that support human activities. The inherent volume change characteristics of naturally expansive materials can lead to cracking and deformations (i.e., failures), which play a substantial role in influencing the stability and geotechnical-related hazards, especially in slopes (Qi and Vanapalli, 2015), underground tunnels (Schullera and Schweiger, 2002), structures (Liu et al., 2016), wellbore (Zhang et al., 1999), and in underground mining (Feng et al., 2022). The problematic results associated with these materials have led researchers to address innovative approaches to mitigate geomaterials' freeze-thaw cycles and shrink-swell behavior, especially in cold regions in our dynamic, fast-paced age. The typical contributing factors that result in the volume change of these materials are the variations in temperature, moisture content, pressure, and chemical reaction, and the details are: (i) the soil and rock masses undergo freeze-thaw cycles because of temperature variations, and these cycles cause phase transitions between water and ice, as the volume of ice is greater than that of water, which may induce the volume expansion; and (ii) some natural soils and rocks contains mineral constituents that could cause volume expansion owing to water absorption and this are the clay minerals and sulfate minerals.

Generally, frost-heaving behavior in geomaterials is one of the leading causes of damage to geo-infrastructure in cold climates, especially in the winter season (Huang et al., 2020). The freeze-thaw settlement of structures on soft clay significantly impacts the geotechnical characteristics of soft soils in cold regions (Konrad and Morgenstern, 1980; Barker and Thomas, 2013). Also, the seasonal and alternating temperatures can cause freeze-thaw cycles in soil and rocks, disturbing engineered underground infrastructure and resulting in potential hazards. Frost heaving varies based on humidity and soil conditions, which can result in non-uniform deformation of railway and highway subgrade constructed on permafrost (Chen Y. et al., 2020). Geo-infrastructure projects built in freeze-thaw geomaterials are one of the most prevalent challenges in the world (Matsuoka, 2001). mentioned that rocks can uptake water during slow freezing, and thus, for frost damage, high initial water content is unnecessary. Consequently, the implications of frost heaving on geotechnical practices in cold regions have been investigated by several researchers. Michaud and Dyke, (2008) discussed the mechanism of bedrock frost heave in permafrost regions, emphasizing the potential threat it poses to engineering design stability.

Shi et al. (2020) analyze the influence of soil frost heaving on the internal force and displacement of foundation pit supporting

structures. Jiang et al. (2023) focused on the frost-heaving characteristics of hydraulic tunnel wall rock in cold regions, emphasizing the spatial distribution and variation of frozen areas and frost-heaving forces. Low temperatures, especially below-freezing points, significantly affect surrounding rock stability in rock engineering projects. Prolonged exposure to negative temperature and freezing conditions alters the deformation and intensity of fractured rocks (Wang and Zhou, 2018). As a result, in the study of rock tunneling in cold regions, the occurrence and expansion of the frost-heaving temperature have been addressed to prevent and reduce frost damage. Studies have shown that the temperature at the entrance section of tunnels is significantly affected by the colder air both inside and outside the tunnel during the cold season, consequently making it the main area susceptible to freezing damage (Yu et al., 2019; Zhou et al., 2021). Zhang et al. (2022) reported that the decrease in temperature in the tunnel causes the freezing of water, and the volume expansion damages the tunnel structure further, causing other forms of freezing damage. This highlights the critical role of low temperatures in driving freezing damage. Furthermore, freezing damage to tunnel foundations encompasses various aspects, including failures in the drainage system, snowmelt and ice formation on roadcut surfaces, foundation seepage, and icing issues (Li et al., 2022).

Natural expansive geomaterials cause many problems in geo-engineering and vary significantly in volume; thus, they expand as they absorb water and shrink as they evaporate (Pooni et al., 2019). Natural expansive geomaterials (expansive soils) are common worldwide, covering about 33% of Sudan, 20% of Indonesia and India, 12% of Syria, and approximately 6% of China (Jalal et al., 2020), and their existence severely slows down geotechnical projects and causes long-term stability problems (Aziz et al., 2015). Several researchers have discussed the inter-particle swelling and intercrystalline expansion mechanism of expansive soils and pointed out that the economic losses due to the alternating shrinkage and expansion behavior of these materials outweigh the damage caused by natural disasters (Jones and Holtz, 1973). Basma et al. (1996) found that cyclic swelling and shrinkage of expansive clays can result in changes in their expansive behavior and microstructure. Lajurkar et al. (2013) highlighted the damaging effects of alternate swelling and shrinkage on structures built on expansive soils. Phanikumar and Singla, (2016) discussed the problems posed by expansive soils and explored the efficiency of fiber reinforcement in reducing swelling and shrinkage. Muthukumar and Shukla (2019) explained that the swelling decreased slightly with an increase in fiber content, while shrinkage significantly decreased with the addition of fibers.

Comparatively, sulfates cover a significant portion of the Earth's surface, making them a crucial area of interest for researchers due to their significance in both geological and environmental contexts. The diverse nature of sulphates and their widespread distribution demands thorough investigation to understand their implications and effects on geo-systems. Joanna, (2012) highlighted that sulphates cover a significant portion of the Earth's surface, including coastal salt lakes, sabkhas, and salt lakes in different regions. Tarragona, (2014) discussed the expansion mechanisms of sulphated rocks and soils, emphasizing the role of gypsum precipitation in discontinuities, which can lead to swelling strains

and geo-structural damage. [Maio et al. \(2014\)](#) investigated the natural occurrence of sulphates in groundwater, suggesting that gypsum formations associated with specific carbonate rocks are the predominant source of sulphates in a particular area. [Samborska et al. \(2013\)](#) studied Triassic carbonate aquifers in Upper Silesia, Poland, and found that sulphate sources included sulphide weathering and gypsum dissolution. [Fontboté et al. \(2017\)](#) focused on sulfide minerals in hydrothermal deposits, which play a crucial role in concentrating metals and triggering the deposition of valuable metals through the precipitation of less economically significant sulfides. These studies represent a diverse range of investigations into sulphates and shed light on their geological significance, expansion mechanisms and natural occurrence on earth.

The behavior of expansive soils, sulfate attack, and freeze-thaw cycles can influence the volumetric expansion of cement structures. Over time, the shrinkage and expansion of expansive soil can cause foundation movement, cracking, and structural damage ([Holtz et al., 2011](#)). Sulfates can penetrate concrete and react with calcium hydroxide and hydrated calcium aluminate to form expanding compounds that can cause cracking, spalling and loss of structural integrity ([Al-Dulaijan et al., 2003](#); [Mamun and Bindiganavile, 2011](#); [Min et al., 2019](#); [Othman et al., 2020](#); [Zhang et al., 2021](#); [Tian et al., 2023](#)). Freeze and thaw cycles can create internal stresses within the concrete and lead to structural damage and failure ([Valenza and Scherer, 2007](#); [Dabas et al., 2021](#)).

The objective of this study is to comprehensively review the expansion behavior and mechanisms of natural expansive materials and frost-heaving behavior in geo-infrastructure. Further, this study will provide an innovative review of: i) the relationship between several potential underlying factors, including moisture content, temperature, and pressure contributing to the volume expansion and shrinkage variations of natural expansive materials; ii) consequences of material expansion and shrinkage for mitigating these challenges in geotechnical engineering, and iii) ongoing efforts to enhance the resilience and sustainability of geo-engineering practices in the face of variable natural expansive material behavior. The rest of the paper is organized as follows: i) [Section 2](#) introduces the swelling-shrinkage behavior of expansive natural materials, and [Section 3](#) covers swelling-shrinkage mechanisms of natural expansive materials; ii) [Section 4](#) focuses on the impact of freeze-thaw cycles and sulfate exposure on the durability of natural and built infrastructure, and [Section 5](#) presents the significance and implications of natural expansive materials in geotechnical engineering applications, and iii) lastly, these sections will be followed by the conclusion section and future research direction section.

2 Swelling-shrinkage behavior of expansive natural materials

2.1 Frost-heaving materials in geotechnical engineering

Many types of soils and rock masses show frost-heaving behavior during the freeze-thaw cycles because of temperature variations when they contain water. Generally, frost heaving

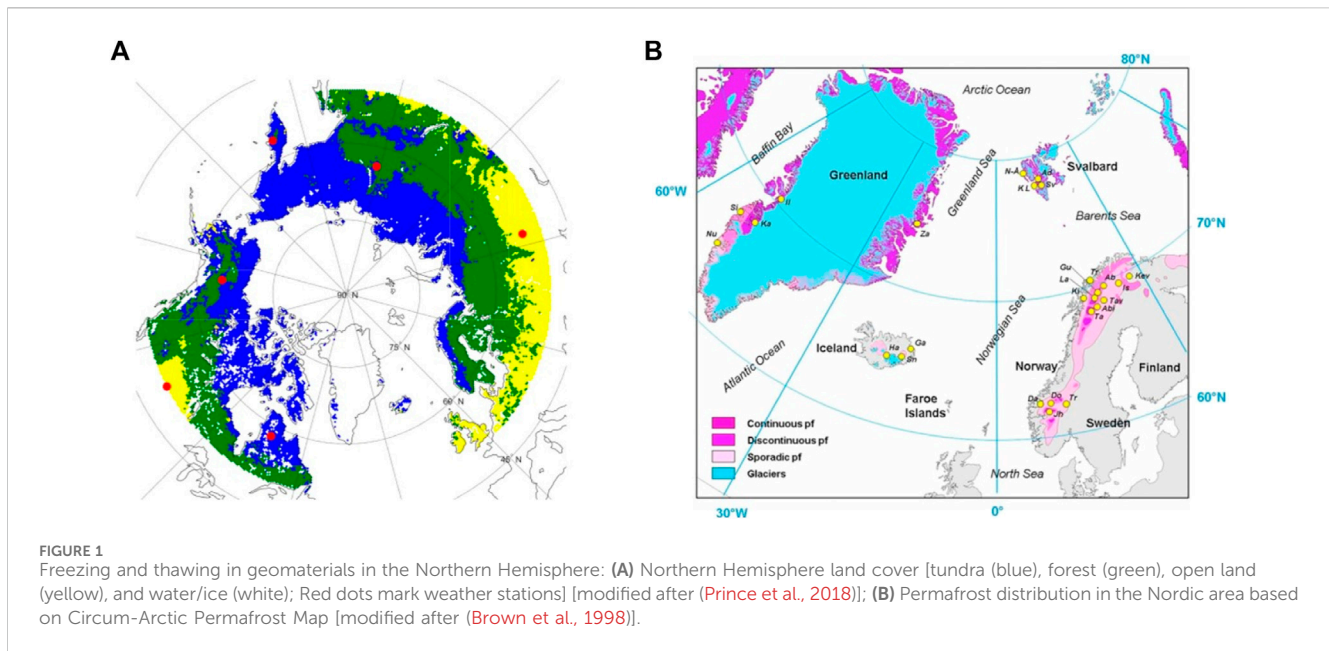
occurs in the northern hemisphere (cold regions) countries like America, Canada, Russia, and the Nordic regions e.g., Denmark, Finland, Iceland, Norway, Sweden, and Greenland ([Brown et al., 1998](#); [Prince et al., 2018](#)) ([Figure 1A](#)), and its influence is a problem of national concern since it delays many engineering projects ([Taivainen, 1963](#)). The effect of frost heaving causes a lot of damage to geo-structures, such as pipelines ([Oswell, 2011](#)), subgrades ([Wu et al., 2018](#)), foundations, tunnels, etc.

The prevalence of seasonal freezing and thawing in the northern hemisphere has far-reaching implications with more than half of the northern hemisphere's land area ([Figure 1A](#)) ([Prince et al., 2018](#)). Within this vast region, a significant portion, precisely one-quarter as well as 17% of the Earth's exposed land surface is characterized by permafrost, where the ground remains frozen at or below 0°C for a minimum of two consecutive years ([Christiansen et al., 2010](#); [Gruber, 2012](#); [Biskaborn et al., 2019](#)). In China, there is an extensive distribution of frozen soil in the northern climates like Tibet, Xinjiang, and Qinghai, where the temperature is low (below 0°C), large frozen depths, and long durations in the soil throughout two-thirds of the time in a year ([Liu et al., 2017](#)). It is reported that engineers working at underground tunnels in these areas in China often observe ice in fractured rock mass at low temperatures, which sometimes causes the fissure volume to expand, resulting in underground instability ([Wang et al., 2016b](#)). Permafrost in the Nordic region can be found in lowland areas with marine sediments, palsas, and peat plateaus, and in many mountainous regions at temperatures near 0.8°C ([Figure 1B](#)), making it highly responsive to climate variations ([Christiansen et al., 2010](#)).

In locations such as Svalbard, northeast Greenland, and the highest mountainous zones throughout the Nordic area, permafrost is slightly colder but still just a few degrees above freezing ([Christiansen et al., 2010](#)). Notably, in Finland, the penetration of frost into glacial soils exhibits distinct regional patterns; thus, in the southern part of the country, frost reaches depths of approximately 1.22 m–1.83 m (4–6 ft), while in the northern part, this freezing phenomenon extends much deeper, ranging from 2.13 m to 3.05 m (7–10 ft) which accounts for more frost occurrence in the northern climate of Finland ([Taivainen, 1963](#)). As a result, boundary markers often shift from their designated positions due to the upward movement of rocks resulting from the volumetric expansion of ice beneath road beds ([Taivainen, 1963](#)).

Extensive research on frost-heaving has been conducted since the early 1990s till date. [Taber \(1930\)](#) and [Taber \(1929\)](#) explored the frost-heaving mechanisms such as the growth of ice lenses in soil. [Mu and Ladanyi, \(1987\)](#) developed models that integrated stress-strain behavior, heat, and mass transport to estimate frost heave. [Matsuoka \(1990\)](#) focused on measuring frost-heaving strains in rocks, observing the influence of surface area on freezing expansion ([Huang et al., 2020](#)). [Dagli et al. \(2018\)](#) investigated the role of suction in water migration to the frost front. [Wang and Zhou, \(2018\)](#) emphasized how jointed rock mass properties can affect frost-heaving pressure due to phase changes. [Osokin et al. \(2000\)](#), [Rekstad et al. \(2013\)](#), and [Liu et al. \(2017\)](#) highlighted the importance of freezing and negative temperatures in soil, leading to volume expansion and negative pressure formation in frozen areas.

Frost heaving is primarily affected by factors such as temperature and pressure, and the details of each factor are



expressed below. However, it is important to recognize that the study of this phenomenon requires a comprehensive understanding of multiple contributing factors (Lu et al., 2021). The change in volume resulting from the freezing of water and the subsequent melting of ice serves as the fundamental trigger for soil deformation within a freezing-thawing environment. Periodic frozen soil is susceptible to temperature variation (Niu et al., 2017; Niu et al., 2017; Lin et al., 2018), and the cyclic pattern of freezing and thawing of soil significantly affects soil strength. Bouyoucos (1920) studied soil physics and chemistry and discovered that water in the soil freezes at multiple temperatures, not just one. Huixin et al. (2012) pointed out that in a closed system, as the freezing temperature rises, the amount of frost heave and the ratio of frost heave relative to the soil mass water content and dry density also increase. Liu et al. (2017) identified frost heave in coarse-grained soils when specific combinations of clay content (the mass fraction of the particle with a diameter less than 0.075 mm), initial moisture, and temperature occurred in seasonal frozen regions.

In rock mass, as the freezing temperature decreases, the unfrozen water film thickness between the rock and the ice decreases, leading to an increase in disjoining pressure (De Gennes, 1985; Rempel et al., 2001; Huang et al., 2020). Wang and Zhou (2018) explained that under freezing conditions and low temperatures, prolonged rock exposure can lead to significant changes in the deformation and strength characteristics of the fractured rock mass. Penner (1959) stated that structures and roadways built on materials highly susceptible to frost, along with their associated expansion, could heave up to 0.61 m. Brimblecombe et al. (2010) stated that the count of freeze-thaw cycles can be determined based on the assumption that rocks freeze solely when the mean daily temperature drops below -3°C , and thawing only occurs when the mean daily temperature rises above $+1^{\circ}\text{C}$. Recently, a novel technique has been developed that utilizes meteorological data to analyze the daily maximum and minimum temperatures. This method entails

monitoring and quantifying freeze-thaw cycles, which are defined by temperature fluctuations either from above freezing to below 0°C or from below 0°C to above freezing (Al-Omari et al., 2015). Table 1 provides a comprehensive overview of the geographic distribution of frost-heaving geomaterials and addresses their implications from a geotechnical engineering perspective.

Freezing can generate high pressure when water is constrained to prevent expansion. This phenomenon can also affect the physical and mechanical properties of rocks. Taber, (1929) and Taber, (1930) mentioned that under atmospheric pressure, when a definite amount of water is cooled, it freezes at 0°C with an expansion in volume at about 10%. Also, in soils, Beskow, (1991) stated that an increase in load pressure leads to soil consolidation, resulting in the squeezing out of water. When the pressure decreases, the soil tends to expand and under these conditions, there is potential for the soil to suck the water required for the volume increase (Black and Hardenberg, 1991). Tarefder and Ahmad (2015) reported that when water enters the road surface, under the intense action of the wheel load, it causes a higher pressure concentration at the weak joint between the aggregate and the asphalt binder, which accelerates the damage process and leads to permanent deformation.

Based on the analysis made, it is recognized that freeze-thaw cycles (temperature variations) and pressure control rock heave and settlement in the foundation when little or no water-ice phase change is involved. Also, the volumetric expansion of frozen water (ice) and the melting of pore ice cause heave in wet geomaterials, which in turn affect the concrete structure and underground space engineering.

2.2 Expansive natural materials in geotechnical engineering

Various types of natural soil and rock masses exhibit a volume expansion behavior. The natural expansive minerals can be divided into two types: i) clay minerals, mainly montmorillonite, illite, or

TABLE 1 Geographic distribution of frost-heaving materials and implication on geo-infrastructure.

Geographic distribution	Location	Frost susceptibility and implications	References
Northern Hemisphere and Arctic Regions	Canada and Alaska: Prairie Provinces (Alberta, Saskatchewan, and Manitoba), Ontario, Quebec.	Long, harsh winters in cold climates, frost-susceptible soils, and large areas of permafrost and seasonally frozen soils pose enormous challenges to the environment and infrastructure. These conditions cause soil instability, impact road and building construction, and affect local ecosystems adapted to freeze-thaw cycles. Water management becomes critical as frozen ground blocks drainage and affects groundwater recharge rates.	Wynn (2006), Stewart et al. (2019), DeBeer et al. (2021), Loranger (2020), Akhmetiev (2015), Panin et al. (2009), Naumov et al. (2020), Tuukka et al. (2020), Bird (2017), Prince et al. (2018)
	Russia: Siberia, Russian Far East.		
	Scandinavia/Nordic regions: Norway, Sweden, Finland, Faroe Islands, Denmark, Iceland, Greenland and Svalbard.		
Temperate Zones	United States: Northern states (Minnesota, Wisconsin, Maine, Michigan, New York);	Moisture-retaining soils during cold winters experience freezing and wetting conditions. The frost-susceptible soils swell and shrink during freeze-thaw cycles, causing significant challenges. In the case of geo-infrastructure, ground movements can cause cracks and instability in buildings and roads. From an environmental perspective, these conditions can damage habitat and soil health, affecting biodiversity and changes microbial activity in soil that affect nutrient cycling and ecosystem.	Donald and Hansen (1974), Baladi and Rajaei (2015), Denny, 1951, Sharifi et al., 2019, Thiry et al. (2014), Isarin (1997), Vaitkus et al. (2016), Kassam (1981), Wang et al. (2017), Xiao et al. (2018), Masaki (2019)
	North Africa: Tunisia, Morocco, northern regions of Egypt, Libya, Algeria, and Western Sahara.		
	Southern Africa: the southern tips of Madagascar, Mozambique, the entire territories of Eswatini, and Lesotho, southern parts of Botswana, Namibia and the great part of South Africa.		
	Europe: Northern and Central Europe (Germany, Poland, United Kingdom);		
	Northern Middle East: northern United Arab Emirates, northern Saudi Arabia, Bahrain, Qatar, Iran, Iraq, Afghanistan, and Turkey.		
	Asia: Northern China, Japan (Hokkaido)		
High Altitude Areas	Rocky Mountains: High elevations in the US and Canada	Cold temperatures and soil moisture cause valleys and areas of standing water to freeze, especially in cold climates where soils are susceptible to frost, posing unique challenges such as cracks in infrastructure, and the environment. Environmental impacts include damage to local ecosystems, particularly those adapted to harsh mountain climates.	Auer et al. (2005), Jaesche et al. (2003), Savi et al. (2015), Hauer et al. (1997), Ives and Fahey (1971), Hewitt, 1968, Dimri and Dash (2011).
	Alps: European Alpine region (Monaco, France, Switzerland, Italy, Liechtenstein, Austria and Slovenia).		
	Himalayas: High-altitude regions (Nepal, Bhutan, Bangladesh, northern India, Pakistan)		

kaolin. Montmorillonite clay will expand significantly as the volume increases, while illite and kaolin clay will have limited expansion. The typical expansive geomaterials which contain montmorillonite are mud rock and bentonite, etc. ii) The other one is the sulphate minerals such as gypsum, anhydrite, calcium thenardite, and anhydrous thenardite. These two types of expansive minerals expand because of the reaction with water.

2.2.1 Clay mineral expansion behavior

Expansive clay minerals are prevalent geomaterials that exist in various regions worldwide, including both humid and arid/semi-arid regions, with their primary mineral constituent being dispersed layered silicate (Cherif et al., 2018). They are heterogeneous in nature and their chemical composition depends on other elements, not only the swelling minerals. The expansion behavior of clay minerals can cause significant damage to geotechnical engineering projects. According to research, the damages associated with expansive clays exceed the average annual damages from floods, hurricanes, earthquakes, and tornados (Jones and Holtz, 1973; Chen, 1975; Simmons, 1991; Jones and Jefferson, 2012; Hyndman and Hyndman, 2014). Bouassida et al. (2022) stated that cracked

foundations, pavements, floors, and basement walls represent common forms of damage induced by expansive clay minerals. Chen (1975) stated that many floor slabs constructed in an expansive clay area crack and sometimes heave due to improper infrastructure design. Also, there have been reported cases where swelling pressure generated by expansive clay caused lateral deflections of basement walls in foundations (Chen, 1975; Elarabi, 2010)

Experimental research in soil mechanics suggests that moisture content, volume increase, swelling pressure, expansion time, surface area, mineral composition and pore morphology are the factors that contribute to the extensive shrink-swell behavior of most expansive clays. The volume of expansive clay minerals tends to increase as they absorb additional water, which is observed in approximately 90% of clays (Chen, 1975; Jones and Jefferson, 2012). When the moisture content of the clay changes, the swelling pressure will increase and cause volume expansion both in the vertical and horizontal directions. Holtz et al. (2011) experimented on the shrink/swell behavior of expansive clay minerals and observed the following: i) the process of swelling and shrinkage are not entirely reversible, ii) shrinkage induces cracks that upon re-

wetting, do not completely close which result in a slight expansion or bulking of the soil, and also allow enhanced access to water for the swelling process. Zhang et al. (2018) studied the expansion characteristics of clay minerals within diverse layers of weathered crust elution-deposited ore bodies and revealed that clay minerals in the humus layer exhibited the highest tendency for swelling. Despite the high swelling potential, if the moisture content of the clay remains unchanged, there will be no volume change; and structures founded on clays with constant moisture content will not be subjected to movement caused by heaving Jones and Jefferson (2012).

Several test results suggest that the swelling pressure increases with respect to decreasing initial water content. However, swelling pressure increases with increasing initial dry density at a controlled initial water content. These trends can either be linear or exponential, according to different research studies (Komine, 2004; Rao et al., 2004; Tu and Vanapalli, 2016). Meanwhile, Tu and Vanapalli (2016) reported that the swelling pressure increase can be attributed to the increased interaction between clay particles due to closer packing. Further, the swelling pressure of clay minerals is primarily affected by their average specific surface area. A larger surface area leads to greater surface forces, which causes significant changes in volume and swelling pressure (Huang et al., 2019; Keskin et al., 2023). Moreover, the duration of expansion and temperature are key factors in determining the linear swelling ratio and initial expansion rate of clay minerals. As the temperature increases, the linear swelling ratio tends to rise which results in a higher initial expansion rate (Chen et al., 2020). Therefore, the swelling of clay minerals is likely to increase with temperature.

On the contrary, it has been recognized that mineralogical composition is an influential factor since different clay minerals have different microstructures in nature (Madsen and Müller-Vonmoos, 1989; Azam, 2003). This variation in microstructure affects the physical and chemical properties of the clay (kaolinite, illite, and montmorillonite), such as its plasticity index, shrink-swell potential, and ion exchange capacity (Shan et al., 2021). Shan et al. (2021) investigated the impact of clay mineral composition on the dynamic properties and structure of artificial marine clay. It was found that marine clays with a high content of montmorillonite showed increased plasticity index (PI) and Atterberg limits. This increase was attributed to the tendency of montmorillonite to more readily adsorb strong and loosely bound water (stern layer) on its surfaces when in a plastic state. Accordingly, understanding the specific mineralogical composition is essential for predicting and managing the behavior of clay in various engineering applications such as soil stabilization and contaminant containment.

Pore morphology substantially influences the swelling behavior of clay minerals (Sarman et al., 1994). Experimented on the pore morphology of clay minerals and concluded that the swelling phase did not only relate to the clay mineral type, but also to the pore morphology. It was found that samples with large pore volumes combined with a high percentage of small-sized pores exhibited high swelling potential. The swelling characteristics of various bentonites with different montmorillonite contents with expansion development time, volume expansion rate, water content, and restricted pressure are summarized in Table 2.

2.2.2 Sulfate mineral expansion behavior

Sulfate minerals are abundant and cover about 25% of the constituent of Earth materials and are also found on other planets (Blatt et al., 1980; Ford and Williams, 2007). They occur mainly in the form of gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) and anhydrite (CaSO_4). Gypsum, which is usually the main source of sulphate-bearing soil is the hydrated form of calcium sulphate and it is primarily detected in geologic structures like veins, beds, and nodules (Alonso, 2012). Anhydrite is reported to exist at depths where there is little or no water (Wang et al., 2019). Fundamentally, the expansion of sulfate mineral is associated with the formation of ettringite and at high sulphate concentrations of gypsum (Tian and Cohen, 2000; Marchand et al., 2001; Müllauer et al., 2013).

The formation of ettringite [$\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$] in soils, is a type of sulfate attack that occurs due to the reaction between sulfate, calcium, and alumina-bearing stages in the presence of water (Figure 2) (Ehwalat et al., 2022). This phenomenon is commonly observed in cement and soils treated with lime, especially in an environment enriched with sulfate (Rajasekaran, 2005; Ehwalat et al., 2022). When calcium and aluminate react with sulfate anions, ettringite can swell up to 250% when form completely and produce insoluble ettringite with increased porosity as the reaction progresses (Zhang et al., 2018; Akula and Little, 2020). According to Ouhadi and Yong (2008), for soil stabilization, the lower solubility of aluminum compounds in a clay fraction is an important source of ettringite formation.

The expansion behavior of sulfated rock formations is more significant than clay or marl rocks when involved in near-surface and underground tunnel excavation (Alonso, 2012; Tarragona, 2014). Structural damage attributed to severe heave and settlement in sulfated natural formations has often been associated with tunneling and bridge abutments when periodically exposed to wetting (Yilmaz, 2001; Alonso, 2012). In open discontinuities in sulphated rock formations, gypsum, upon contact with water molecules at a molecular level, expands and undergoes a volume increase of about 62% creating ice crystals (Wittke, 2006; Alonso, 2012). This percentage volume increase causes the crystals to fill the discontinuities, thereby resulting in heaving/expansion behavior in rocks (Figure 3).

Gypsum is susceptible to rapid dissolution upon contact with water; as a result, its availability causes the spontaneous collapse of individual caverns and migration of voids, eventually leading to subsidence of the overlying ground surface (Yilmaz, 2001). When gypsum acts as a cementing agent, the dissolution of the cement can result in the breakdown of the soil structure (Abduljawad and Al-Amoudi, 1995; Yilmaz, 2001). The leaching of gypsum and anhydrite creates cavities in the subsoil, which may induce the collapse of light structures without prerequisite warning (Yilmaz, 2001; Azam, 2007).

Zanbak and Arthur (1986) discussed the mechanism of hydration expansion and deformation of anhydrite rock, and the study showed that the molar volume of anhydrite increases after water absorption, and the volume expansion could be 62.6%. Madsen and Müller-Vonmoos, (1989) carried out theoretical and experimental studies on the microscopic scale from the perspective of mineralogy on the interaction between

TABLE 2 Swelling characteristics of various bentonites with different montmorillonite contents.

Soil/rock	Clay mineral content %	Expansion time (hr)	Volume expansion ratio %	Water content %	Restricted pressure kPa
Bentonite (Komine, 2004)	Montmorillonite 48	~15–70	~6–360	13.8	~6–941
Bentonite (Komine, 2004)	Montmorillonite 69	Over 150	~10–250	13.1	~10–2032
Bentonite (Komine, 2004)	Montmorillonite 80	~1–15	~16–120	29.5	~10–2098
Bentonite (Komine, 2004)	Montmorillonite 76	~10–150	~15–180	25.6	~10–2040
Bentonite (5%) (Komine and Ogata, 1999)	Montmorillonite 48	~5–30	~46–77	19.4	~21–36
Bentonite (10%) (Komine and Ogata, 1999)	Montmorillonite 48	~15–44	~67–90	17.6	~31–43
Bentonite (20%) (Komine and Ogata, 1999)	Montmorillonite 48	144	~117–235	17.0	~56–112
Bentonite (30%) (Komine and Ogata, 1999)	Montmorillonite 48	~144–648	~209–375	14.6	~100–180
Bentonite (50%) (Komine and Ogata, 1999)	Montmorillonite 48	720	~350–585	17.5	~167–280

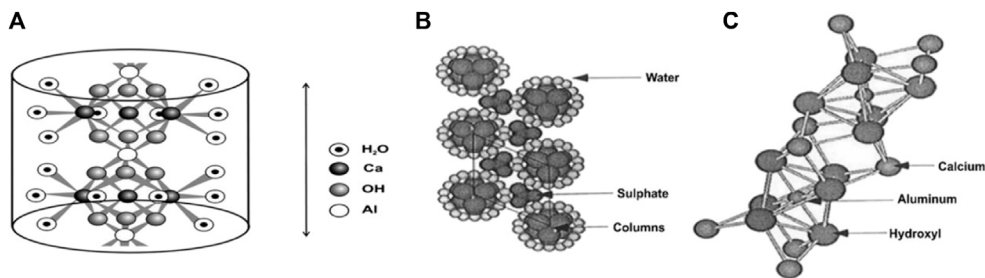


FIGURE 2 Schematic of ettringite formation: (A) ettringite’s chemical structure, (B) columnar formation of ettringite, (C) existence of aluminum and calcium polyhedral [modified after (Ehwailat et al., 2022)].

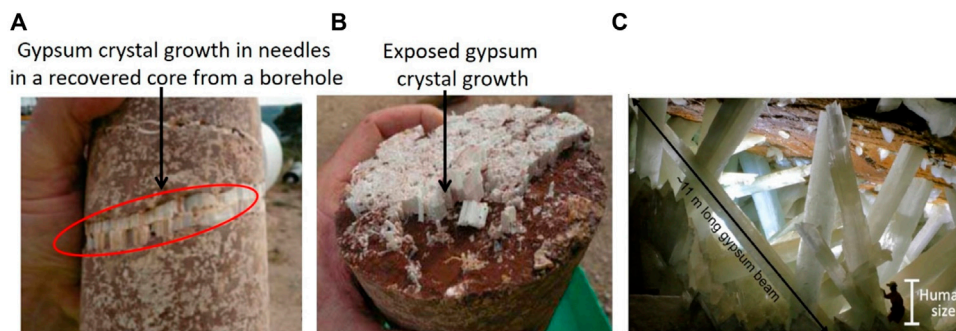


FIGURE 3 Gypsum crystal growth: (A) expansion of gypsum crystal within a rock vein, (B) gypsum crystals after opening with hands [modified after (Tarragona, 2014)]; and (C) Gigantic gypsum crystals in Naica’s Crystal Cave (Chihuahua, Mexico) [modified after (Van Driessche et al., 2019)].

clay particles, anhydrite, and gypsum crystal. Kaiser (1975) studied the growth and expansion of ettringite and anhydrite crystals in solution, and believed that with the change of thermal equilibrium and hydrodynamics, the anhydrite expansion curve showed a logarithmic curve growth form. Barnhoorn et al. (2005) used the residual strain scanning method to study the texture characteristics of anhydrite rocks in the Swiss Bibiani Islands, which is of great significance for underground engineering works, such as mining and tunnels.

Rauh and Thuro (2007) performed powdery swelling tests, thin slice analysis, electron microscope scanning analysis, x-ray diffraction, and specific surface area analysis on gypsum rocks in three different places, and reported that swelling is related to the crystallinity of CaSO_4 , the larger the crystal size, the smaller the expansion capacity. Azam (2007) studied the geological and engineering issues involved in the expansion and compression of the anhydrite-gypsum transition along the Arabian Gulf coast, some key experimental stages of anhydrite have evaluated their swellability using volume morphological changes, and the gypsum compression index and rebound index were determined. Alonso (2012) conducted softening and swelling experiments of clay-containing anhydrite rocks under the effect of water evaporation and studied the effect of sulphate concentration in solution on swelling.

The analysis suggests that when the sulphate minerals absorb water, the moisture content in gypsum increases, which causes swelling and when the moisture content decreases, it shrinks, leading to structural cracks in civil engineering and other construction works.

3 Swelling-shrinkage mechanism of natural expansive materials

3.1 Frost-heaving expansion mechanisms

The expansion mechanism of frost-heaving soil arises from the interaction between three frost actions: water supply, frost-susceptible soil composition, and temperature as the primary factors (Taber, 1930; Penner, 1959; Black and Hardenberg, 1991; Guthrie et al., 2007; Liu et al., 2017). Heaves are more likely to happen in soil with unique textures, such as loam, silt, and clay, which are moisture-retaining.

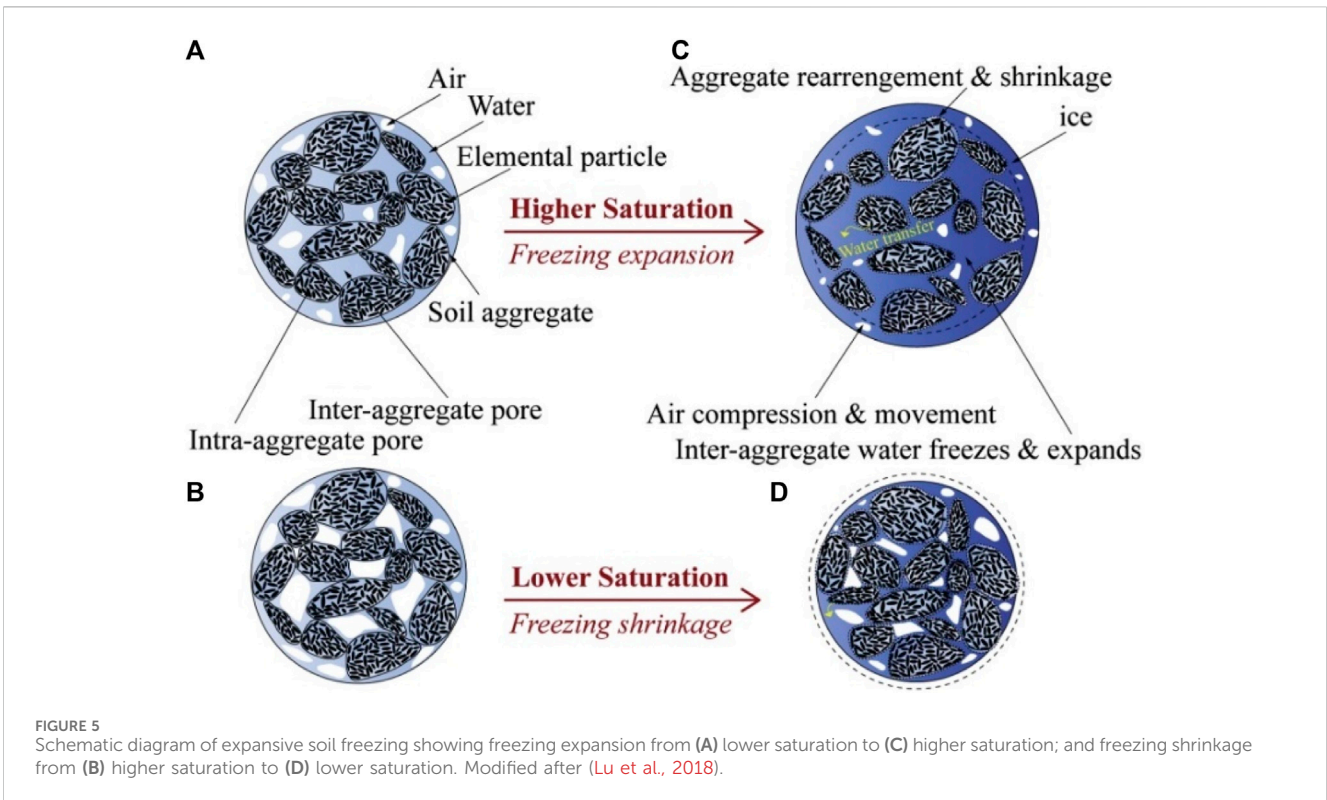
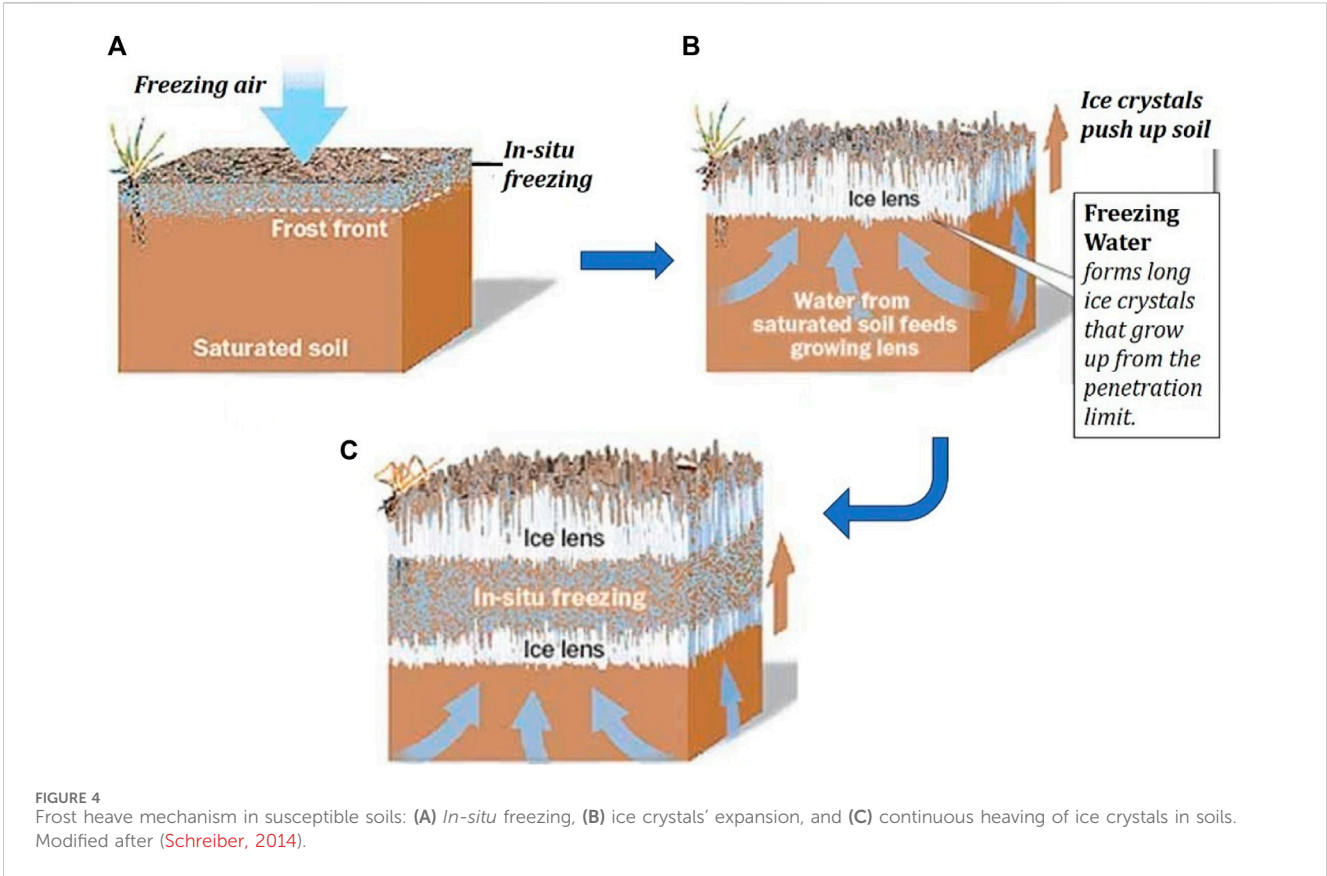
Freeze-thaw cycles are common in soils due to fluctuating temperatures. When soil layers freeze, pore water movement is transferred from unfrozen areas to negative regions, which leads to the expansion of the soil's volume and the development of negative pressure (Beskow, 1991; Black and Hardenberg, 1991; Osokin et al., 2000). In these cold regions, pore water crystallizes and forms ice in the pores, sometimes forming ice lenses (Konrad and Morgentern, 1980; Kozłowski and Nartowska, 2013; Schreiber, 2014). This phenomenon can lead to significant frosts and a decrease in the engineering properties of the soil. In cold climates, the cyclic freezing and thawing processes strongly influence the durability and performance of geo-infrastructure (Tian et al., 2019). The physical and mechanical properties of soils, including expansive soils, change significantly due to freeze-thaw cycles (Yang et al.,

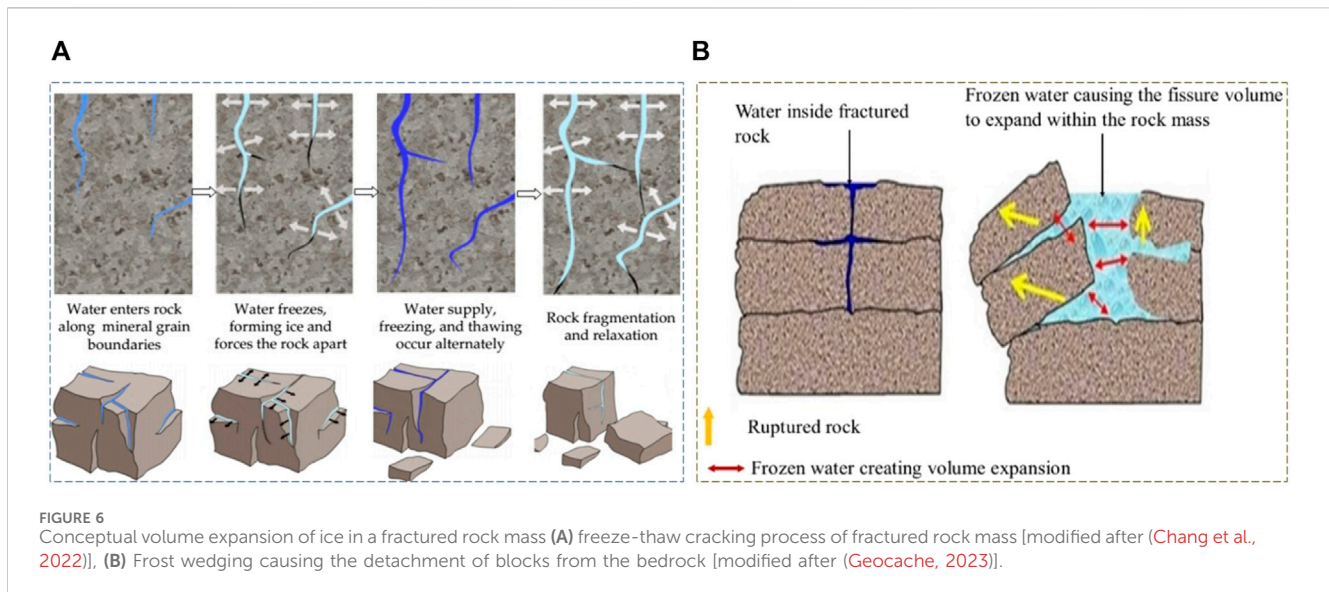
2021). Freezing and thawing cycles result in a decrease in the soil's bulk density and penetration resistance (Unger, 1991). The freeze-thaw process induces uneven stresses within the soil, which create cracks, fractures, and joints in most clay soils, leading to a significant increase in permeability (Eigenbrod, 1996; Fouli et al., 2013; Aksakal et al., 2021). However, coarser soils show a slight change in permeability (Eigenbrod, 1996). As shown in Figure 4A (Schreiber, 2014), when the ice expands within the frozen ground, it induces a soil volume increase of 9%, as proposed by the pore water pressure hypothesis. With high soil moisture content, the surrounding regions will continually provide moisture to the frozen area through capillary action.

This process subsequently contributes to additional ice volume expansion, ultimately leading to frost heaving at the base of the soil. (Guthrie et al., 2007; Liu et al., 2017). The expansion of the frozen water (ice lens) within the soil will exert upward pressure from the penetration limit and induce deformation, which in turn lifts the *in-situ* frozen soil (Figure 4B) (Schreiber, 2014; Wang and Zhou, 2018). As the temperature gradually decreases over an extended period at a point where the water supply to the lens stops, the frost front drops down until it encounters the saturated soil and creates another ice lens, which creates consecutive volume expansion within the soil (Figure 5) (Schreiber, 2014). The process can continue and cause vulnerability to the infrastructures in the affected area. Consequently, (Alonso et al., 1987; Alonso et al., 1990; Alonso et al., 1999), Adem and Vanapalli (2015), and Lu et al. (2018) and reported the expansion mechanism in expansive soil during freezing at different degrees of saturation in porous materials. Figures 5A,B represent particle types and arrangements in unfrozen expanded clay at higher and lower saturations, respectively.

Clay particles form aggregates that control macropore space, while elementary clay particles regulate the micropore distribution within the aggregates, creating dual porosity. When soil with higher saturation freezes (Figure 5C), the pores between aggregates expand due to the growth of ice lenses, resulting in the compression and rearrangement of soil aggregates. Low-temperature suction forces the water within the aggregate out, which causes drying-induced shrinkage (Lu et al., 2018). This compensatory shrinkage is insufficient to balance the expansion of the growing ice, resulting in an overall increase in soil volume. In contrast, under lower saturation conditions (Figure 5D), the volume expansion of water between the aggregate and ice is contained by the air present in the pores.

In rock mechanics, the presence of joints and fissures significantly affects the geological stability of a rock mass, especially in fractured rock mass, where they play a pivotal role. As the strength of rock is impacted by these discontinuities, the properties of jointed rock are particularly susceptible to the influence of ice within these joints during freezing temperatures (Wang and Zhou, 2018). The frost heave of a rock mass is subject to various factors: temperature, rock frost susceptibility, surrounding rock grade, porosity, and external water supply conditions (Wang et al., 2016a). Joint water in its free state condenses by undergoing a phase change to ice due to negative temperature, exhibiting an expansion coefficient of 9% (Wang et al., 2016a). The water freezing within rock joints initiates a volumetric expansion of the joint filling. This expansion is constrained by the surrounding rock mass, leading to an increase in frost-heaving pressure as a result of the phase transition. If this pressure exceeds the rock mass





strength, the jointed rock will fracture and break apart as shown in Figure 6. Given a homogeneous rock medium, the frost heaving ratio is the relationship between volume increment and the original rock volume. This ratio is affected by the 9% volume phase transition process, influencing the rate of frost heave as shown in Eq. 1 (Wang et al., 2016a):

$$\eta = \frac{\Delta V}{V} \quad (1)$$

where η is the frost heaving ratio, ΔV is the volume increment of the frost heave, and V is the volume of the original rock.

Additionally, when a rock is exposed to negative temperatures and freezing conditions for a long time, the deformation and intensity properties of the fractured rock mass change greatly. Such occurrences pose threats to constructions such as tunnels, shafts, storage caves, and other infrastructure (Luo et al., 2015; Wang and Zhou, 2018)

In contrast, the above analysis shows that the frost heaving in geomaterials does not promote water flow, causing high hydraulic conductivity. As geomaterials freeze, their porosity decreases and restricts capillary flow. This phenomenon can prevent water ingress from forming ice lenses that cause volume expansion of the geomaterials, resulting in an uplift at the surface. On the contrary, the freeze-thaw process of these natural expansive materials makes it difficult to control water movement in the underground support environment.

3.2 Expansion mechanism of natural geomaterials

3.2.1 Expansion mechanism of clay minerals (montmorillonite)

The expansion of the interlayer space in clay minerals is due to the hydration energy forces associated with the interaction of the particles (Karpiński and Szkodo, 2015). Clay mineral expansion (montmorillonite) is generally considered to be mainly intergranular and lattice expansion (Figure 7).

The intergranular expansion is mainly caused by the absorption of water in the aqueous medium by the surface of the clay particles under the effect of electrostatic attraction, which results in the expansion of the soil or rock due to the increase of the thickness of the combined water film (Figure 7A). The expansion of the crystal layer (lattice) occurs when there is a change in the expansive mineral under the action of water or in a humid environment. Water enters the mineral either by becoming an inherent part of the mineral composition or by occupying the spaces within its crystal lattice structure (Tuller and Or, 2003), which causes the mineral volume to expand significantly (Figure 7B). This phenomenon makes it difficult to control water movement in foundations and underground support environments.

3.2.2 Expansion mechanism of sulfate minerals

The mechanism that leads to the expansion of sulphate minerals is primarily attributed to the evaporation-based and gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) precipitation through an aqueous solution in the presence of anhydrite (CaSO_4) (Tarragona, 2014).

The evaporation-based mechanism requires a boundary that interacts with an atmosphere of lower relative humidity than the water potential in the soil or rock. Alternatively, the rate of evaporation and the gypsum solubility also affect this mechanism. The evaporation rate controls moisture removal, while the limited solubility of gypsum restricts the amount that can be dissolved. Nonetheless, the extent of precipitation is constrained by the combined effects of low solubility and controlled evaporation rates. The limited precipitation primarily occurs on or near the evaporation surface, rather than within the volume of the geomaterial and, therefore, initiates a small mass of precipitated gypsum (Tarragona, 2014; Butscher et al., 2015).

Gypsum precipitation through an aqueous solution with anhydrite can lead to larger volumes of gypsum formation, posing greater engineering risks compared to evaporation-based mechanisms (Alonso, 2012; Tarragona, 2014; Butscher et al., 2015). For instance, since natural calcium sulfate-rich water is supersaturated and anhydrite has higher solubility

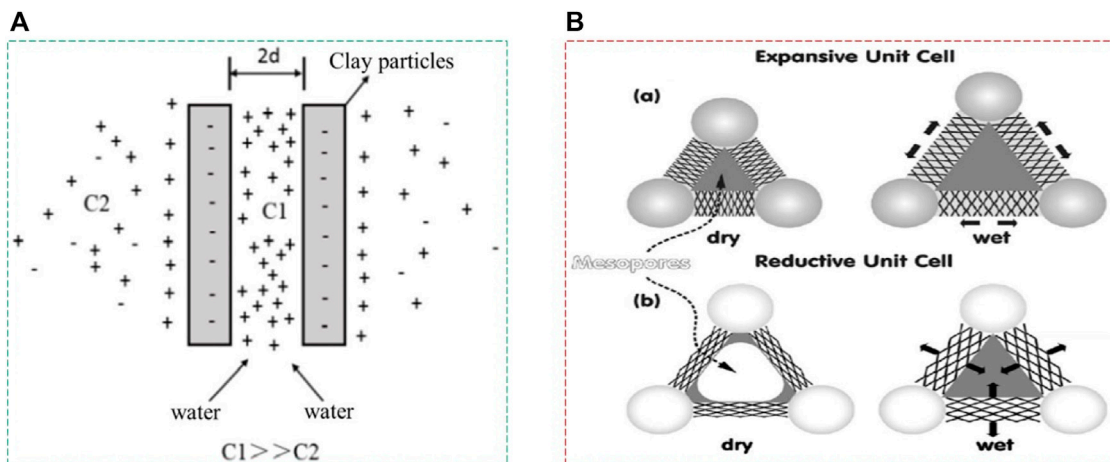


FIGURE 7 Schematic illustration of expansion mechanism of montmorillonite minerals: (A) Intergranular expansion, (B) Lattice expansion. Modified from (Tuller and Or, 2003).

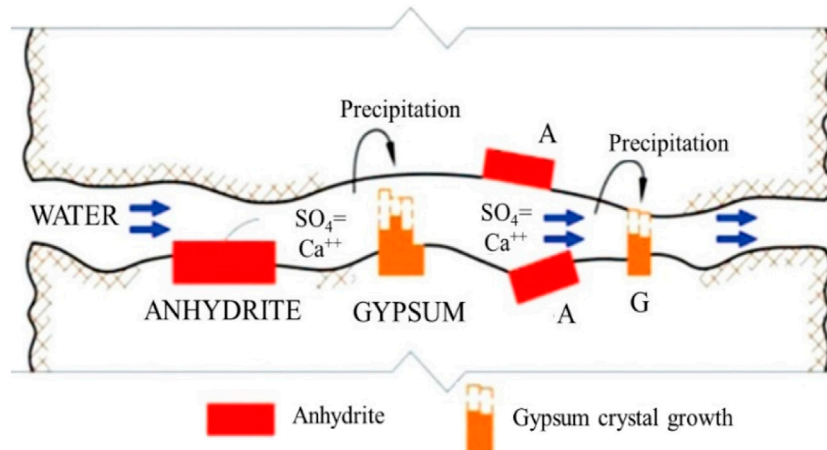


FIGURE 8 Conceptual model for gypsum precipitation. Source: (Tarragona, 2014).

compared to gypsum at temperatures below 56°C, the water in contact with anhydritic claystone at the active layer will dissolve anhydrite and subsequently lead to the precipitation of gypsum (Kontrec et al., 2002; Alonso, 2012; Tarragona, 2014). Afterward, the water becomes supersaturated with respect to gypsum, which causes the excess dissolved calcium sulphate to precipitate as gypsum crystals.

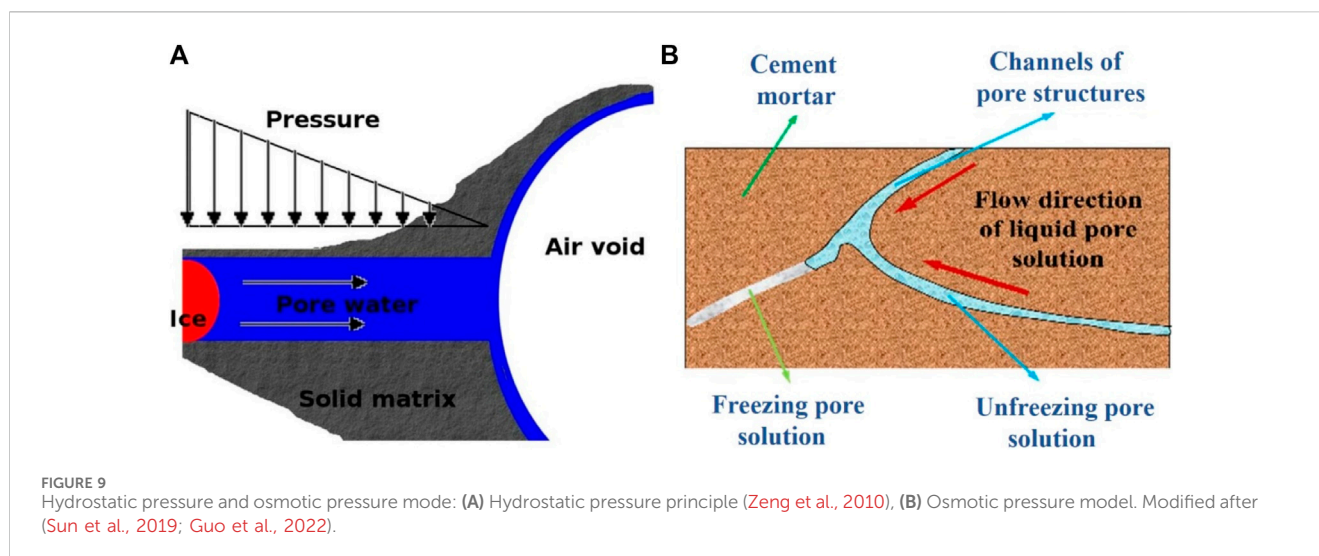
In practical terms, the excess hydrated gypsum can be transported in an aqueous solution or precipitate within available voids in rocks. This action can exert pressure on the rock mass and push it apart, while potentially triggering the expansion of discontinuities and inducing swelling strains (Figure 8) (Alonso, 2012; Tarragona, 2014; Butscher et al., 2015). As presented in Figure 8, the analysis shows that hydrated gypsum can be transported in an aqueous solution and fill fracture spaces in the rock mass, making it difficult to control water movement in the geo-structural environment.

4 Impact of freeze-thaw cycles and sulfate exposure on the durability of natural and built infrastructure

4.1 Damage mechanism of freeze-thaw cycles in cemented structures

The primary mechanism of freeze-thaw damage in cemented structures is described by both the hydraulic pressure theory and the osmotic pressure theory, and both mechanisms are attributed to concrete deterioration (Powers, 1949; Powers, 1975; Hudec, 1991; Pigeon et al., 1996; Valenza and Scherer, 2007; Zeng et al., 2010; Dabas et al., 2021; Guo et al., 2022).

According to Powers and Darcy's law, the hydraulic pressure theory explains the effects of low temperatures on concrete (Powers, 1949; Powers, 1975). When concrete is exposed to low temperatures, the outer layer of the concrete freezes first. This freezing causes the



liquid water within the concrete to migrate through capillary pores due to the volume differences between ice and liquid water. Precisely, ice occupies a greater volume than liquid water, creating a differential pressure that drives the migration (Valenza and Scherer, 2007; Dabas et al., 2021; Guo et al., 2022). As the temperature continues to drop, the volume of ice within the concrete increases. This increase in ice volume compresses the remaining liquid water, generating significant compressive stress in the pores of the concrete. Simultaneously, ice expansion induces tensile stress in the concrete matrix (Guo et al., 2022) (Figure 9A). If the tensile stress exceeds the ultimate tensile strength of the concrete, microcracks begin to generate (Zeng et al., 2010). These microcracks generated can compromise the structural integrity of the concrete which can lead to long-term durability issues. In spite of the knowledge addressed by the hydraulic pressure theory, it does not fully explain certain phenomena. For instance, it does not account for the expansion observed in ordinary concrete during freezing or the behavior of non-expansive liquids when they freeze (Rønning, 2001; Yu et al., 2017).

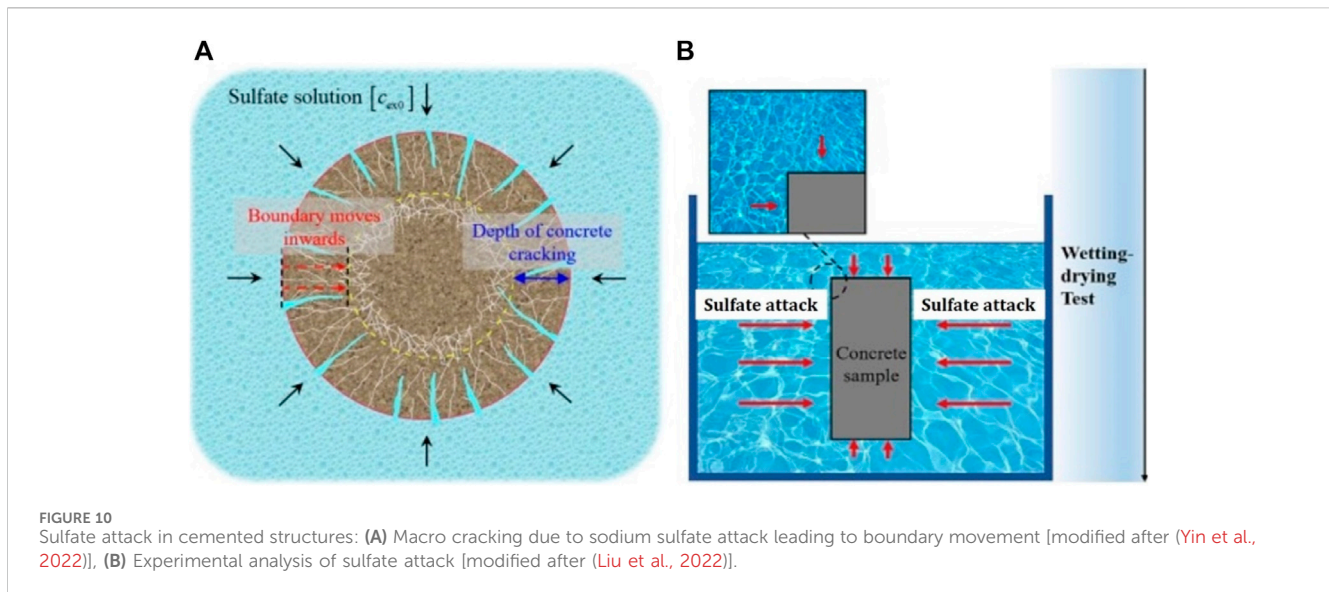
Studies have discussed the osmotic pressure theory, which involves specific salt ions in concrete (Powers, 1949; Powers et al., 1953; Powers, 1975; Hudec, 1991; Valenza and Scherer, 2007). According to this theory, the complex pore structure of concrete results in varied migration rates of ions and water which leads to the development of osmotic pressure and interior damage. When unfrozen water transitions to ice, osmotic pressure is generated because the vapor pressure of liquid water becomes higher than that of ice (Figure 9B). This pressure is directly related to the concentration of the solution; as the concentration increases, so does the osmotic pressure. Conversely, the amount of ice formation has an inverse relationship with osmotic pressure, with the pressure value being highest at a specific concentration of the solution (Washburn, 1921; Guo et al., 2022). Basically, osmotic pressure theory emphasizes that the migration and distribution of salt ions and water within the porous structure of concrete can generate significant internal pressure during freeze-thaw cycles. This can cause damage such as microcracks, especially in areas where the solution concentration is at maximum coupling values (Figure 9B).

To mitigate cracking in concrete due to freeze-thaw cycles, an effective method will be to reduce hydrostatic pressure by decreasing the spacing between pores. This may be accomplished through the use of air-entraining agents, which introduce tiny air bubbles into the concrete mix. These air bubbles create additional space in the concrete that can accommodate the expanding ice, thereby reducing the overall pressure and preventing damage. For instance, in regular concrete, the pressure exerted by the freezing water causes the concrete to expand in volume. Nevertheless, in air-entrained concrete, the presence of micro-pores created by the air-entraining agents allows the ice to form within these spaces, leading to a contraction rather than expansion (Sun and Scherer, 2010).

4.2 Impact of sulfate attack on cemented structures

Concrete deterioration occurs due to sulfate ions reacting with hydrated cement composites in pore solution, leading to expansion and corrosion in geo-infrastructure (Figure 10), and this reaction forms expansion phases like gypsum and ettringite, as well as corrosion types such as calcium alumina, magnesium sulfate complex, and carbon-sulfur calcium silica stone corrosion (Al-Dulaijan et al., 2003; Mamun and Bindiganavile, 2011; Min et al., 2019; Othman et al., 2020; Zhang et al., 2021; Tian et al., 2023). Sulfate attack in concrete is affected by the availability of sulfate ions, moisture content, temperature fluctuations, and exposure duration.

Basically, sulfate attack in concrete involves physical and chemical reactions (Chen et al., 2020). In the physical reaction, sulfate ions penetrate concrete pores, causing crystallization-induced expansion, leading to internal cracking, which can generate tensile stress and lead to progressive loss of mechanical strength (Tulliani et al., 2002; Oualit and Jaubertie, 2019; Brekailo et al., 2023). The deterioration process originates from two main sources: internal and external attacks. The internal attack results from sulfate within the concrete itself, while external sources include various environmental factors like soils, groundwater, transport

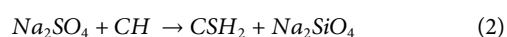


fluids, river water, seawater, coastal areas, and acid rain (Neville, 2004; Zhao et al., 2020).

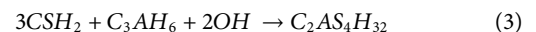
Water serves as a carrier that allows sulfate ions to infiltrate the concrete matrix over time. This infiltration is further heightened by wetting and drying cycles, which can occur naturally or as a result of environmental conditions such as temperature and water table fluctuations. At higher temperatures, water travels at a faster rate along with sulfate ions, which accelerates the chemical reaction between the sulfate and the hydration products of the cement (Ikumi and Segura, 2019; Chen et al., 2020; Zhu et al., 2023). This acceleration causes swellable compounds to form more quickly and increases the rate of deterioration. This reaction results in the formation of expansive compounds such as gypsum and ettringite (Ikumi and Segura, 2019; Chen et al., 2020). These compounds exert pressure within the concrete matrix, causing internal cracking, expansion, and ultimately deterioration of the concrete structure. However, areas with warmer climates may experience a more rapid progression of sulfate attack than colder environments where temperatures are lower and reactions proceed more slowly.

During sulfate attack, particularly assuming sodium sulfate (Na_2SO_4) as the sulfate source, the following chemical reactions (Zuo et al., 2012; Ikumi and Segura, 2019).

Gypsum formation (CSH_2): when sulfate intrudes into concrete, it reacts with the concrete hydration products, such as calcium hydroxide (CH) and calcium silicate hydrate (CSH) to form (CSH_2) (Zhu et al., 2023). The chemical reaction formula as shown in Eq. 2 (Al-samawi and Zhu, 2020):



Ettringite formation ($C_6AS_3H_2$): when gypsum reacts with calcium aluminate phases, such as Monosulfate (C_4ASH_{12}), Tricalcium aluminate (C_3A), Hydrogarnetto (C_3AH_6) etc. in concrete components, the reaction will result in the formation of ettringite (Zhu et al., 2023). The chemical reactions formula as presented in Eq. 3 (Al-samawi et al., 2023):



The reaction process of these compounds causes concrete expansion, and microcrack formation, and facilitates the entry of harmful ions, accelerating concrete damage.

5 Significance and implications of natural expansive materials in geotechnical engineering applications

5.1 Significance and implications of frost heaving in geomaterials

Frost heaving, a critical geotechnical concern in cold regions, causes structures built on geomaterials to uplift due to freezing temperatures. It alters soil and rock properties by impacting load-bearing capacity, weakening their strength integrity. This poses a serious threat to both surface and underground geo-infrastructures like tunnels, foundations, pipelines, roads, etc., and, however, necessitates a profound understanding of accurate design and mitigation for geotechnical considerations and engineering practices. Table 3 provides a comprehensive summary of the freeze-thaw cycle effects on expansion materials, highlighting their factors and implications in geotechnical engineering.

Further, in cold weather, especially during negative temperatures, the expansion of ice within fractures acts like a stabilizing agent that binds the fractured rock mass together and enhances its stability as well as any structure adjacent to or within it. This phenomenon is often referred to as frost wedging. In the context of underground openings such as tunnels or mines, the presence of ice filling the fractures can provide additional support and reinforcement to the surrounding rock mass. It helps maintain the structural integrity of the openings and minimize the risk of collapses or instability. In frost-susceptible soils, natural rubber latex (NRL) can significantly improve durability against the adverse effects of wetting and drying (w-d) cycles in cement-stabilized

TABLE 3 Summary of freeze-thaw effects of natural expansive material and their implications in geotechnical engineering.

Category	Region/Context	Factors/Conditions	Implications	References
Freeze-thaw effects	Northern Hemisphere (cold regions: America, Canada, Russia, Nordic regions)	Temperature variations, presence of water, soil type	Frost heaving delays engineering projects; damage to pipelines, subgrades, foundations, tunnels	Brown et al. (1998), Prince et al. (2018), Taivainen (1963), Oswell (2011), Wu et al. (2018)
Permafrost	Northern Hemisphere (e.g., Canada, Russia, Nordic regions)	Temperatures at or below 0°C for at least 2 years	Ground remains frozen, impacting infrastructure stability	Biskaborn et al. (2019), Christiansen et al. (2010), Gruber (2012)
Frost penetration	China (Tibet, Xinjiang, Qinghai)	Low temperatures (below 0°C), extensive frozen soil distribution	Ice in fractured rock mass causes instability during thawing.	Liu et al. (2017), Wang et al. (2016b)
Frost depth variation	Finland	Regional temperature differences, glacial soil types	Frost reaches different depths in southern and northern regions, causing boundary marker to shift from their original position.	Taivainen (1963)
Soil deformation	Various regions with seasonal freezing	Temperature variation, soil moisture content, clay content	Soil deformation due to freeze-thaw cycles affecting the strength.	Lin et al. (2018), Niu et al. (2017), Niu et al. (2020), Huixin et al. (2012), Liu et al. (2017)
Frost Heave in rock mass	Cold regions	Freezing temperature, rock frost susceptibility, water supply conditions	Increased frost-heaving pressure can result in surface cracking and jointed rock mass fracturing, which increases the risk of rock falls and landslides.	De Gennes (1985), Huang et al. (2020), Rempel et al. (2001), Wang and Zhou (2018), Luo et al. (2015)
Hydraulic and osmotic pressure theories	Cemented structures	Low temperatures, capillary pore water migration, ice formation	Concrete deterioration due to freeze-thaw cycles	Powers (1949), Powers (1975), Dabas et al. (2021), Guo et al. (2022), Hudec (1991)
Mitigation strategies	Cemented structures	Use of low water-to-cement ratio mixes and air-entraining agents to introduce tiny air bubbles, applying melamine-formaldehyde coatings to concrete reduces water absorption and protects against freeze-thaw damage, using high-quality aggregates that are durable and resistant to frost action.	Reduction of hydrostatic pressure and cracking in concrete	Sun and Scherer (2010), Yeon and Kim (2018), Liu et al. (2024)

soil, particularly when subjected to cyclic tensile loads (Udomchai et al., 2021; Hoy et al., 2023). The NRL forms films that infiltrate and fill the pores and microcracks within the soil-cement matrix. This infiltration not only strengthens the bond between soil particles and cement but also enhances the overall durability of the geo-infrastructure. By preventing the propagation of microcracks and reducing permeability, these NRL films provide a robust barrier against freeze-thaw cycles (Udomchai et al., 2021; Hoy et al., 2023). It is important to note that this stability enhancement is particularly significant during cold seasons when freezing occurs. However, during warmer seasons or when the ice melts, rock mass maintenance and monitoring are crucial to ensure continued stability.

5.2 Significance and implications of expansive natural geomaterials

Natural expansive geomaterials with high shrink-swell potential play a crucial role in geotechnical engineering. These materials exhibit unique properties that can significantly affect infrastructure stability and environmental concerns. Therefore, this section discusses the significance and implications of clay minerals and sulfate minerals in geotechnical engineering, drawing upon relevant research and findings.

5.2.1 Implications of using clay minerals

Clays have complex structural properties, including their small-sized expansive surface areas, which control the solid soil fraction's reactivity, act as water reservoirs in soils, and maintain plant-friendly moisture levels in hot and dry environmental conditions (Villieras et al., 1997). Clay minerals are widely used in geotechnical engineering as impermeable barriers and underground seals due to their low hydraulic conductivity, which effectively retains fluids and prevents the rapid convective transport of various leachates from waste disposal sites (Villieras et al., 1997; Met and Akgun, 2015). However, swelling clays pose risks in geotechnical engineering projects due to stability concerns (Villieras et al., 1997). Understanding the properties of clay minerals and their relationship and interaction with water is critical to characterizing clay material applications. One effective approach to addressing these issues is the chemical grouting method, which involves injecting materials such as lime, cement, and silica fume into the soil. This method has been extensively studied and has been shown to improve soil stability, reduce permeability, and enhance load-bearing capacity, making the soil more suitable for supporting structures (Zhao et al., 2014; Puppala and Pedarla, 2017; Al-Gharbawi et al., 2022; Dharini et al., 2023).

Al-Gharbawi et al. (2022) investigated the swell and contraction behavior of expansive soils, primarily composed of montmorillonite, in response to water content changes. The study focused on using

TABLE 4 Summary of bentonite applications in geotechnical engineering.

Category	Conditions	Significance	References
Bentonite clay minerals	Small particle size, low hydraulic conductivity, stability under certain temperatures, and moisture interaction	Bentonites particularly serve critical roles in geotechnical applications, primarily as impermeable barriers and sealing materials. They control soil reactivity, act as water reservoirs, and stabilize ground conditions.	Villieras et al. (1997), Met and Akgun (2015), Klik et al. (2022)
Applications of Bentonite	High cation exchange capacity and swelling pressure, and long-term durability	Bentonite is used for its low permeability and high cation exchange capacity in geo-infrastructure projects such as soil stabilization, landfill liners, and nuclear waste repositories.	Komine (2004), Klik et al. (2022), Liu et al. (2019), Abdalqader et al. (2023), Svensson et al. (2017)
Challenges and Considerations	Quality control measures, environmental factors (temperature, pH, salinity, microbial activity), long-term durability	Ensuring consistent quality of bentonite is crucial for reliable performance in engineering applications, especially under changing environmental conditions and long-term use in nuclear waste containment.	Magnus et al. (2020), Kolstad et al. (2004), Mazzieri et al. (2017), Laine and Karttunen (2010)

TABLE 5 Summary of natural expansive materials and expansion behavior in geo-infrastructure.

Category	Conditions	Implications	References
Clay mineral expansion	Moisture content, volume increase, swelling pressure, mineral composition, and pore morphology influence shrink-swell behavior.	Expansive clay minerals are heterogeneous and cause damage like cracked foundations, pavements, and floor heaving.	Jones and Jefferson (2012), Holtz et al. (2011), Zhang et al. (2018), Shan et al. (2021)
Sulfate mineral expansion	Formation of ettringite, gypsum precipitation through evaporation or aqueous solutions, and solubility dynamics influence expansion.	Sulfate minerals (e.g., gypsum, anhydrite) expand due to ettringite formation, causing structural heave in tunnels and bridges.	Blatt et al. (1980), Marchand et al. (2001), Alonso (2012), Kaiser (1975), Barnhoorn et al. (2005), Tarragona (2014)
Impact of Sulfate attack in cemented structures	Sulfate ion availability, moisture content, temperature fluctuations, and exposure duration influence concrete degradation.	Sulfate attack on concrete causes expansion and deterioration through reactions with hydration products (e.g., gypsum, ettringite).	Al-Dulaijan et al. (2003), Oualit and Jauberthie (2019), Ikumi and Segura (2019), Zhu et al. (2023)

5%, 7%, and 9% lime, cement, and silica fume to stabilize soils. The results showed that stabilization reduced free swell and swelling pressure by about 65% and 76%, respectively. Additionally, grouting with silica fume improved the bearing capacity of footings by 64%–82% for soils treated with 5% and 9% silica fume, respectively. Dharini et al. (2023) investigated the treatment of expansive clay soils using hydrated lime powder and sodium silicate. The study identified 10% lime as the optimal content based on standard proctor and unconfined compressive strength tests. Different proportions of sodium silicate (2%, 4%, 6%, 8%, 10%) were examined while maintaining the optimal lime content. The results from California Bearing Ratio (CBR) tests indicated that soil treated with lime exhibited a CBR value 5.2 times higher than untreated soil, and soil treated with both lime and sodium silicate showed a CBR value of 7.86 times higher than untreated soil. While undisturbed clay barriers have historically shown higher performance in containing chemical waste, identifying thick natural barriers is not always feasible (Met and Akgun, 2015). As a result, compacted clay liners have become essential in municipal and hazardous waste landfill lining systems (Met and Akgun, 2015).

In addition to the use of clays as soil barriers, several clay minerals have useful applications in geo-infrastructure. Bentonite is particularly known for its low permeability, which makes it ideal for certain geotechnical applications. For instance, it is used for its high cation-exchange ability, allowing effective binding and retaining ions making it useful for soil stabilization and geo-infrastructure projects (Klik et al., 2022). When bentonite absorbs water, it hydrates and swells, forming a stable gel structure that enhances

its adsorption capacity. The resulting swelling pressure creates a dense structure that fills capillary pores and effectively seals fractures, cracks, and void spaces, thus preventing the migration of radioactive materials over long periods (Komine, 2004; Liu et al., 2019; Klik et al., 2022). Bentonite enhances grout waterproofing and strength, prevents bleeding, and forms a low-permeability hardened material purposely for sealing groundwater inflow and reinforcing fractured rock (Peila et al., 2011; Jinpeng et al., 2018; Benyounes, 2019; Zhou et al., 2020; Abdalqader et al., 2023). Aside from these traditional applications, bentonite have been used as buffer materials in high-level nuclear waste repositories to prevent radioactive waste from leaching into groundwater, and potential escape into the environment (Swedish Nuclear Fuel and Waste Management, 1992; Johnson et al., 1994; JNC DI, 1999; Ito, 2006; Sellin and Leupin, 2013; Tripathy et al., 2015; Liu et al., 2019).

Ensuring consistent quality of bentonite clay is critical, but challenging due to natural variations in its composition. Variations in mineral content, particle size and moisture content can affect its swelling characteristics and performance. This requires strict quality control measures, including periodic testing and characterization of bentonite batches, to ensure consistency and reliability in engineering applications (Kiviranta and Kumpulainen, 2011; Svensson et al., 2017; Magnus et al., 2020). Under changing environmental conditions, bentonite buffer can undergo physical and chemical changes over an extended period that can affect its performance as a sealant or barrier material, especially in geological repositories. Factors such as chemical interactions with surrounding materials, changes in temperature (high temperatures) and

humidity, specific pH and salinity conditions, and microbial activity can reduce its performance. In nuclear and geotechnical engineering, long-term durability is an important issue, specifically for applications such as nuclear waste containment, where materials need to maintain their integrity for thousands of years (Kolstad et al., 2004; Laine and Karttunen, 2010; Mazzieri et al., 2017). Table 4 summarizes the geotechnical applications of bentonite, highlighting its high cation exchange capacity and low permeability which make it effective for soil stabilization and geo-infrastructure projects.

5.2.2 Implications of using sulfate minerals

Gypsum is extensively used in geotechnical engineering for diverse purposes such as embankment and subgrade backfill material, cement additive, building material, treatment agent for expansive soils, and soft soil reinforcement (Shen et al., 2012; Rashad, 2017; Jiang et al., 2018; Rosales et al., 2020; Pu et al., 2021). Gypsum plays a crucial role in cement manufacturing by preventing or slowing down the rapid setting of cement particles, a phenomenon known as flash setting (Aakriti et al., 2023). Its application as an additive material to stabilize expansive soils (clay soils) has gained significant attention due to its widespread availability, cost-effectiveness, minimal carbon emissions, and its ability to improve water resistance (Toksöz Hozatlıoğlu Yılmaz, 2021; Ma et al., 2022).

Relatively, recycled gypsum's positive impact on soil stabilization is evident through its influence on various engineering and environmental factors, including compaction characteristics, consistency, strength, deformation, compression, shear, expansion properties, and long-term durability in the past decades (Pu et al., 2021). However, the number of comprehensive studies exploring the efficiency of gypsum in soil stabilization remains relatively limited, with notable contributions from researchers (Yılmaz and Civelekoglu, 2009; Kiliç et al., 2015). In contrast, combining gypsum with other materials offers a wide range of applications in the construction industry. For instance, fly ash-lime-gypsum bricks are used as a substitute for traditional clay bricks in construction, and their application contributes to soil conservation, pollution reduction, and an increase in the consumption of fly ash and gypsum (Jayasudha and Niranjan, 2014).

Table 5 provides a summary of various natural expansive materials, highlighting how their expansion behavior can affect geo-infrastructure. The analysis indicates that clay mineral expansion, influenced by factors such as moisture content and volume increase, leads to shrink-swell behavior and can cause significant damage to foundations. Sulfate mineral expansion results in structural heave in tunnels and bridges. Additionally, sulfate attack in cemented structures causes concrete expansion and deterioration through reactions with hydration products like gypsum and ettringite.

6 Conclusion

This paper reviews the intrinsic and extrinsic contributing factors and significance of natural expansive materials and their impact on geo-infrastructure. Additionally, this work

emphasizes the critical role these materials play in engineering practices, with a particular focus on their involvement in geotechnical-related hazards, such as freeze-thaw cycles, damage, and sulfate attack in underground cemented structures, as well as their applications in geotechnical engineering. The following deductions were made:

- i. Frost heaving is prevalent in the Northern Hemisphere, Arctic regions, temperate zones, and high-altitude areas. In these geographical locations, when a significant amount of water within the geomaterials and concrete structures freezes, they can expand by approximately 10% of their original volume. This expansion can enlarge fractures and void spaces in geomaterials and concrete structures during the thawing process, which can contribute to structural instability in these regions.
- ii. The freeze-thaw cycle is influenced by variations in temperature and pressure. In rock mechanics, prolonged exposure of rocks to low temperatures ($\leq 0^{\circ}\text{C}$) and high temperatures ($> 0^{\circ}\text{C}$) can lead to significant changes in the deformation and strength characteristics of fractured rock masses. Additionally, when pressure decreases, soil tends to expand, while increasing pressure causes soil to shrink. Therefore, it is recognized that freeze-thaw cycles make it difficult to control settlement in geo-infrastructure and rock heave in underground space engineering.
- iii. Expansive clay minerals (notably montmorillonite) are widespread in both humid and arid regions which pose significant geotechnical hazards, surpassing damages caused by natural disasters. The expansion mechanism of clay minerals, driven by hydration energy and water absorption into interlayer spaces and crystal lattices is complex which makes it difficult to control water movement in underground excavation and foundation engineering.
- iv. Bentonite is being explored as a buffer material in high-level nuclear waste repositories for storage due to its unique swelling and sealing properties to provide a safer containment and isolation of radioactive wastes over extended periods in deep underground environments. Also, bentonite provides a reliable substitute for cementitious materials in geo-infrastructure and can enhance grouted rock stability, waterproofing, and rock strength, in addition to contributing to soil stabilization.
- v. Sulfate minerals, particularly gypsum, interact with water, resulting in a theoretical 62% volume increase while transforming into ice crystals. This transformation process can fill rock discontinuities. Moreover, the formation of these ice crystals exerts pressure on the surrounding rock, causing heaving and potentially leading to geo-infrastructure damage.
- vi. Sulfate attack in concrete structures and geo-infrastructure involves a chemical reaction between sulfate ions and hydrated compounds, leading to expansion, corrosion, and the formation of gypsum and ettringite phases. The expansion of sulfate minerals is influenced by evaporation-based precipitation and anhydrite-aqueous solution mechanisms, making it crucial to assess risks and implement mitigation strategies for geological and engineered structures.

7 Future research directions

This review highlights several key areas for future research, particularly in understanding the frost-heaving behavior in rocks, clay minerals, sulfate minerals, and concrete structures, as well as the shrink-swell behavior and expansive mechanisms in geomaterials within geotechnical engineering. Extensive studies have explored frost-heaving mechanisms, considering factors such as ice lens growth, stress-strain behavior, temperature, pressure, and load conditions. Critical elements in this complex process include moisture content, temperature variations, and cyclic freezing-thawing patterns. However, to achieve effective engineering design practices, key research gaps related to expansive materials should be prioritized in future studies:

- i. Frost heaving in tunneling and rock engineering is a significant concern due to its impact on rock mechanical integrity, driven by pressure changes during freezing and thawing. However, the mechanisms of frost heaving in deep underground rock openings remain poorly understood and warrant further investigation.
- ii. There is a knowledge gap regarding how the expansion, shrinkage, and chemical reactions of sulfate minerals in geomaterials and cemented infrastructures can induce significant reinforcements under varied loading and environmental conditions. The influence of expansive natural materials on geo-infrastructures can be profound, often resulting in foundation cracks, structural tilting, and compromised integrity. Repairing damage caused by expansive natural materials can be costly and time-consuming, necessitating proper site assessment and engineering solutions.
- iii. Expansive soils also impact the environment, causing soil erosion, sedimentation in water bodies, and altered groundwater flow patterns. To mitigate these effects, geotechnical engineers should implement strategies such as moisture control, proper drainage, moisture barriers, and foundation designs that accommodate soil movement by using experimental, numerical modeling, and field investigations.
- iv. Ongoing research using emerging technologies to better understand natural expansive materials and their interactions with water, which cause shrink/swell behavior should be investigated through advanced soil and rock testing

methods, predictive models, numerical modeling, and microstructural characterization. These approaches will enable geotechnical engineers to predict material behavior, identify internal mechanisms, and develop strategies to minimize the impact on geo-infrastructure, resulting in safer and more resilient construction.

- v. Strict measures must be tailored to ensure that building codes and regulations, which include comprehensive guidelines for construction in regions susceptible to expansive soils and freeze-thaw cycles, are strictly adhered to. These measures are crucial for safeguarding the safety and structural stability of buildings and infrastructure.

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Nomenclature

$CaSO_4 \cdot 2H_2O$	Gypsum
$CaSO_4$	Anhydrite
Na_2SO_4	sodium sulfate
Na_2SiO_3	sodium metasilicate
CSH_2	gypsum formation
CH	calcium hydroxide
CSH	calcium silicate hydrate
$C_6AS_3H_2$	ettringite formation
C_3A	tricalcium aluminate
C_4ASH_{12}	monosulfate
C_3AH_6	hydrogarnetto
η	the frost heaving ratio
ΔV	volume increment of the frost heave
V	volume of the original rock