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Effects of Expansive Clay Content on the Hydromechanical Behavior of Liners Under Freeze-Thaw Conditions

Ahmed M. Al-Mahbashi * and Muawia Dafalla

Department of Civil Engineering, College of Engineering, King Saud University, Riyadh 11421, Saudi Arabia
* Correspondence: aalmahbashi@ksu.edu.sa or ena_almahpashi@hotmail.com

Abstract: In several geotechnical and geoenvironmental projects, fines containing expandable clay minerals such as expansive clay (EC) were added to sand as sealing materials to form liners or hydraulic barriers. Liner layers are generally exposed to different climatic conditions such as freeze-thaw (FT) during their service lifetime. The hydromechanical behavior of these layers under such circumstances is of great significance. In this study, the impact of fine contents of expansive soil on swelling, consolidation characteristics, and hydraulic conductivity under FT conditions is examined. Different clay liners with 20%, 30%, and 60% of EC content were designed. The specimens were initially subjected to successive FT cycles up to 15 in close system criteria. The results revealed that volumetric strains attained during successive FT cycles are proportional to the content and nature of expanding minerals (i.e., montmorillonite) and reached a 4.5% magnitude value for the liner with 60% clay. Vertical strains during wetting conditions have been reduced by about 90% after the first FT cycles, which implies significant destruction in the soil structure. The yield stress indicated a 60% change, along with increasing FT cycles. The hydraulic conductivity during an extended period of 100 days shows significant changes and deterioration due to FT actions. The outcome of this study will help to predict the lifetime behavior and performance of the liner, taking into account the stability under frost conditions.

Keywords: fine content; expansive clay; clay minerals; sand; freeze-thaw cycles; compressibility; hydraulic conductivity

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1. Introduction

Expansive soils have great attention to be used as a filler material in designing natural or environmentally friendly liners. The brilliance of this concept is the mineralogical composition of these soils, which consists of expandable minerals. The fine content and, in turn, the expandable mineral content in a fill material have a significant impact on the hydromechanical performance of clay-sand liners during freeze-thaw cycles, impacting hydraulic conductivity, structural stability, and overall durability.

Sand-clay lining systems are utilized as barriers to prevent the passage of leachates and liquids, thereby protecting downstream soil, groundwater, and surface water from dangerous pollutants. The liner system is usually found at the bottom of a landfill or as a cover layer. In both circumstances, the system is subjected to different climatic fluctuations, such as freeze-thaw cycles. Because of the length of exposure, cover layers are the most affected by freeze-thaw activities in places with freezing seasons.

The majority of governmental environmental control authorities require a hydraulic conductivity of no more than 10^{-7} cm/s in design requirements. Some authorities may

accept slightly different values (2×10^{-6} to 10^{-7}) according to Tiongson and Adajar [1]. To maintain this flow level throughout the landfill facilities, variations in hydraulic conductivity must be tracked and monitored during field tests.

Hydraulic conductivity may vary depending on the exposure conditions. To see if particular exposure conditions could affect hydraulic conductivity, the researchers conducted extensive research on common sand-expansive clay combinations and clays in a semi-arid region [2,3].

Zou and Boley [4] investigated the influence of freeze-thaw on the compressibility of fine-grained soils. Wenhu et al. [5] found that FT induces significant and non-uniform changes in soil index features and consolidation parameters, such as pre-consolidation pressure, compression, and swell indices.

Al-Mahbashi et al. [6] and Othman and Benson [7] conducted research on the influence of freeze-thaw on the hydromechanical behavior of clay soils and liners in a semi-arid location. There has been a bit of research on how freeze-thaw cycles alter the behavior of expansive clay-sand mixtures and the content of expandable clay minerals. When adverse weather conditions are expected, this type of research can assess the integrity, durability, and functionality [8,9]. Hydraulic conductivity is mostly determined by fine content, which also influences compressibility and stability. There has been very little research on the effect of fine content on compressibility during freeze-thaw cycles.

According to Pei et al. [10], within the initial elastic compression range, compression indices (including the recompression index, pre-consolidation pressure, and compression index) are independent of moisture content changes but increase after FT conditioning and are dependent on the volume of the soil's large pores. Ren et al. [11] revealed that clay compressibility is affected by the starting moisture content, cooling temperature, and number of FT cycles. The compressive strain increases under the same vertical pressure when the cooling temperature declines, the initial moisture content rises, or the number of FT cycles increases. Clay sand liners are predicted to react differently because the sand makes up the majority of the mixture. It was therefore necessary to investigate the compressibility and vertical strain changes that could occur as a result of FT. This also affects the liner's hydraulic conductivity, which is the primary design parameter. Several studies have used hydraulic conductivity as the key criterion to assess the efficiency of various sand-clay and sand-bentonite liners [2,3,6,12,13].

Stress and freeze-thaw cycles have a considerable impact on the hydraulic conductivity of clays [14,15]. The observed increase in hydraulic conductivity as a result of exposure to freeze-thaw cycles varies mostly by soil type; clays with high initial hydraulic conductivity show relatively minor changes as a result of freeze-thaw action [14]. Repeated freezing creates a layered structure, allowing water to pass between micro and macro pores and increasing hydraulic conductivity. Othman [14] and Sterpi [16] reported and summarized considerable increases in hydraulic conductivity for diverse clays resulting from freeze-thaw activities.

It is worth indicating that there are no studies that evaluate the effect of FT conditions on the hydromechanical behavior of designed liners, taking into account the effects of fine contents with mineralogical composition and long-term performance of liners. Therefore, the need for the current study is considered of great importance. This research aims to emphasize the impact of fines containing expandable minerals on the swelling, compressibility, and long-term hydraulic performance of cover layers that are anticipated to sustain light to heavy loads under freeze-thaw exposure conditions. Successive freeze-thaw cycles were applied on soil specimens before commencing testing (i.e., 0, 1, 5, 10, and 15). Varied liners with varied fine contents (expanding minerals) were examined to cover the practical range used in geoenvironmental and geotechnical applications. Soil porosity, compressibility, and

deformation, or volume changes under expected frost conditions, have a substantial impact on hydraulic conductivity and are both important in cover and lining design protocols. The hydraulic conductivity was evaluated over an extended period of time to examine the sustainability of designed layers in the long run of serviceability.

2. Materials and Characterizations

Al-Qatif clay combined with fine to medium poorly graded sand as per ASTM D2487 [17] was used in this investigation to compose clay sand liners. This clay is known for its expansiveness and high plasticity.

For the expansive clay, the mineralogical composition of this soil obtained from x-ray diffraction analysis was presented in Figure 1; the analysis shows the existence of expandable clay minerals. Based on this analysis and as estimated from the beak intensity method, the percent of expandable clay minerals reaches up to 34.7. In addition, a study conducted by Rafi [18] for the same soil revealed that the concentration of palygorskite is in the range of 5% to 33% while the montmorillonite content reaches up to 23%. The peaks that indicate the presence of expandable minerals in some zones are not visible; the smoothening process and software used for this analysis show the possibility for montmorillonite minerals occurring before 20 and around 28 of 2θ. The specific gravity, liquid limit, and plastic limit of this expansive clay with other primary geotechnical characteristics are presented in Table 1. Due to its high plasticity, according to ASTM D4546 [19], this clay has a large potential for expansion: approximately 20% [20–22]. The percent passing sieve #200 for this clay was in the range of 65–94% and is classified as inorganic clays of high plasticity (CH) according to the unified classification system. Chittoori et al. [23] used volumetric particle size analysis to investigate comparable clay for the macro and micro pores.

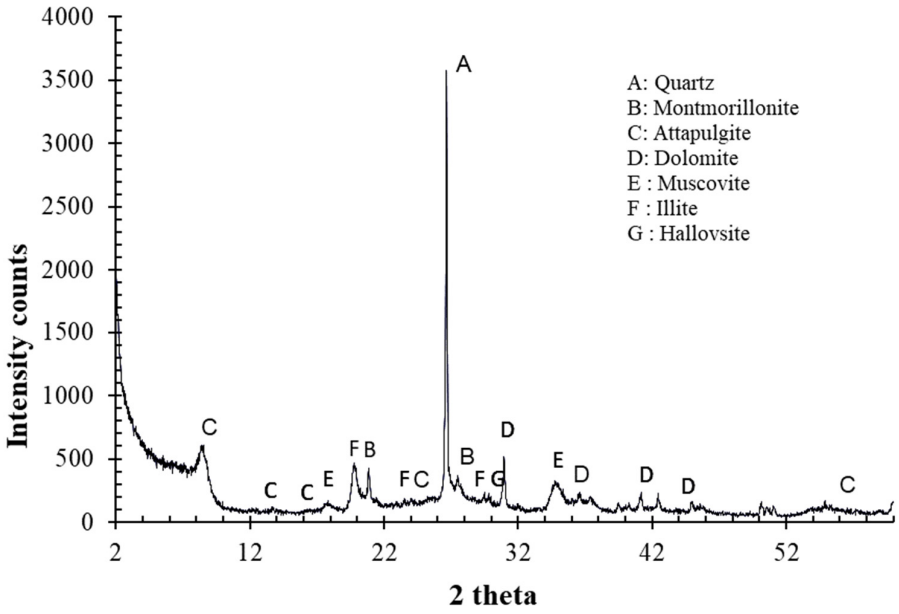


Figure 1. Mineralogical compositing of fine content.

Table 1. Basic characterization for tested material.

Test	Value
Expnasive soil	
Specific Gravity, *Gs*	2.70
Liquid Limit, LL (%)	160%
Plastic Limit, PL (%)	60%
Shrinkage Limit, wsh (%)	12%
% passing Sieve No. 200	65–95%
Unified soil classification	CH
Swelling potential [19]	16–25%
Swelling pressure [19]	450–800 kN/m^2
pH value	7.6
Sand	
Cation exchange capacity, meq/100 gm	55.80
Specific Gravity, Gs	2.86
Unified soil classification	SP
Uniformity coefficient, Cu	1.745
Curvature coefficient, Cc	0.945
Particles size range	0.1 mm–0.6 mm

In order to characterize the sand with regard to gradation, two characteristics are typically determined: the uniformity coefficient and the coefficient of concavity were reported and presented in Table 1. The sand was classified as poorly graded sand (SP) according to ASTM D2487 [17]. As an inert material, the mineralogical composition of this sand has been carried out, and two peaks were shown for quartz and calcite [24]. The chemical composition of this sand is also shown in Table 2 [25].

Table 2. Chemical composition for tested material.

Element	Expansive Soil	Sand
K^+ (%)	1.8	-
K_2O (%)	2.2	>0.1
Al (%)	3.3	-
Al_2O_3 (%)	6.3	0.25
Si (%)	8.1	-
SiO_2(%)	17.3	99.43
Ca^{2+} (%)	0.7	-
CaO (%)	0.9	0.16

The sand is combined with expansive clay to form mixtures of clay content as 20%, 30%, and 60%. Depending on the type of clay (i.e., expandable clay minerals) and its index properties, a certain amount of clay is advised for the design of liners. The proposed values were chosen to be within the practical range that meets the requirements of hydraulic conductivity of designed liners and covers [3,6]. According to Al-Mahbashi et al. [3], adding 20% of Al-Qatif clay to the sand can achieve a 10^{-7} cm/s hydraulic conductivity, which is a typically required value for approving sand-clay liners. Depending on the kind of barrier that is needed, lower hydraulic conductivity can be used. Achieving particular values is significantly influenced by the porosity of the sand utilized.

In compliance with ASTM D698 [26], the usual compaction proctor tests were carried out in the laboratory for the tested liners. As per these results, the maximum dry density and the optimum moisture content were determined and presented in Table 3.

Table 3. Optimum moisture content and maximum dry density.

Fines or Clay Content in a Liner	Optimum Moisture Content, %	Maximum Dry Density, gm/cm^3
20%	13.6	1.86
30%	13.7	1.84
60%	25.0	1.60

3. Experimental Program

3.1. Preparing the Samples

In this study, twenty, thirty, and sixty percent of the highly plastic natural clay from the Al-Qatif region of Saudi Arabia was combined with poorly graded sand. Using traditional ASTM D 698 [26] compaction curves, a predetermined amount of water (Table 1) was added to the mixture to reach the desired moisture content. The field condition and placement need to be recognized during testing [27]. Using a hand-operated jack, the identical specimens were compacted to the matching maximum dry density (as per the compaction curve) in 50 to 80 mm diameter and 20 to 40 mm height.

Prior to compressibility and hydraulic conductivity testing, several of these samples were frozen and thawed several times. After being tightly wrapped in plastic wrap, the initial groups of compressed specimens were frozen and thawed in a confined environment. First, the specimens were placed in the freezer cabinet and frozen for approximately 24 h. The temperature in the controlled cabinet was kept at −23 °C ± 2 °C. ASTM D560 [28] specifies this temperature, which has also been used in previous studies [29]. After the first freezing, the samples were defrosted in a humidity room at +23 °C ± 1 °C for a further 24 h. The humidity box was completely sealed and supplied with 100% humidity. One freeze-thaw cycle is represented by the full freezing and thawing process, which was repeated up to ten times in a row. Following the freeze-thaw cycles, each sample's weight and water content were recorded. The samples' heights and diameters were measured with a digital caliper to determine the variance in the sample volume.

3.2. Swelling and Compressibility Testing

The swelling and consolidation properties of various soils were investigated for compacted specimens prior to and following FT cycles. This test was conducted using a one-dimensional odometer device that meets ASTM D4546 [19] and ASTM D2435 [30] standards. The specimens were placed in the device cell and originally submerged in distilled water with a light surcharge load for at least 24 h, or until the vertical strain disappeared. The specimens were then incrementally loaded in increments up to 800 kPa, with each increment maintained until vertical deformation ended. Following that, the weight on the specimen was gradually reduced in comparable increments to obtain the rebound curve. All soil consolidation curves were plotted. The vertical strain, compression index, and swelling indicators retrieved from the test results were calculated.

3.3. Hydraulic Conductivity Testing

The ASTM D 2487 [17] and ASTM D7928 [31] were used as approved ASTM testing methodologies for hydraulic conductivity measurements in the laboratory. Falling head permeability experiments were performed on compacted specimens with a clay content of 20% and 30% that had not been subjected to freeze-thaw cycles (natural) and on specimens that had been subjected to freeze-thaw cycles (FT). The tests were carried out in the laboratory under a constant room temperature of 21 ± 2.0 °C. As previously stated, the specimens are the same size: 80 mm in diameter and 40 mm in height. The specimens contain wire mesh-fitted porous stone layers attached to the top and bottom. The specimen

was attached to the flow routes and hydraulic conductivity setup within the cell. The load arm is attached to the load cap that sits above the soil specimen. A little surcharge was applied, and flooding lasted five to seven days. The inundation was carried out with distilled water. The ASTM D5856 [32] standard was used to conduct the falling-head test. A flushing exit was installed in the cell to ensure that no air bubbles obstructed the flow or penetration channel. In this study, the flow is considered steady when four (4) consecutive measurements are taken with minimal fluctuation. After establishing a consistent flow, the sample is allowed to continue passing through the elevated tank. Throughout the test period, the volume and time of water outflow were monitored. During the discharge or flow, hydraulic conductivity measurements were taken one to three times each day. This is accomplished by monitoring the graded burette's level, which is linked to the tank's outflow level. This is a long-term, daily activity that is repeated.

4. Results and Discussion

The results achieved by conducting this experimental program are discussed in detail in the following subsections.

4.1. Volumetric Strains During FT Cycles

The volumetric strains during the FT cycles for the 60% fines were observed for the two extremes of freeze and thaw and reported as high as 4.5% for the first freezing cycle and moved towards −2.5% for the thawing at the 15th cycle. The fluctuations of the volumetric strain can be brought down by increasing the number of FT cycles as shown in Figure 2a. The size of fluctuation is limited to an absolute value of 2% to 1% for the fine content of 30% and 20% (Figure 2b,c). In this study, the fine content is rich in montmorillonite minerals; the volumetric strains reach about 4.5% in magnitude during FT, as mentioned before. These volumetric strains are proportional to the content of expanding minerals that existed (fine content). Interpreting this behavior under the influence of FT cycles is made more difficult by the swelling nature of such expansive soil minerals (i.e., montmorillonite). As shown by the pore size distribution measured by mercury porosimetry, microcracks are prone to propagating, and soil structure is destroyed [29]. Increasing the number of cycles reduces the volumetric strain. The number of cycles required to significantly reduce the volumetric strains may be dependent on other factors related to the interlayer forces between clay particles or the clay fabric.

4.2. Effect of FT Cycles on the Swelling and Compressibility of Tested Liners

The development of the vertical strain is a found function of time, and more time is needed to attain the maximum vertical strain when the clay content is more. Figure 3a–c present the measured vertical strains during wetting conditions with time. Freezing and thawing can disrupt structural integrity, scatter clay particles, and form fissures in the liner material [6]. This might result in the closure of pores and voids inside the clay, reducing its performance. Al-Mahbashi et al. [6] discovered that the freeze-thaw effect is linked to the clay's plasticity and rate of expansion. They discovered that expansive clays with high concentrations of montmorillonite and smectite minerals were the most influenced by freeze-thaw cycles. It is worth indicating that after the first FT cycle, the vertical strains reduced by 80 to 90%, and this revealed the level of structural destruction attained during a single FT cycle. After the fifth cycle of FT, the effect becomes a stable trend.

Figure 4 presents the typical consolidation curve with the main parameters defined in shapes and notations. The compressibility index is the slope along the loading phase, while the swell index is the slope of the curve while off-loading the samples. The 60% and 30% clay contents indicated a very slight change in the compression index before and

after freeze-thawing cycles; unlike the 20% clay, the compression index is significantly influenced. This is likely due to the contribution of sand grains in stress sharing and support of exerted loads. We can conclude that the clay-sand mixture behaves like clay with regard to supporting stresses when the clay content is 30 or over. The sand grains are engulfed within the clay with no edge-to-edge contact or influence on the stiffness of the mixture. The swell index is seen as similar for all clay content.

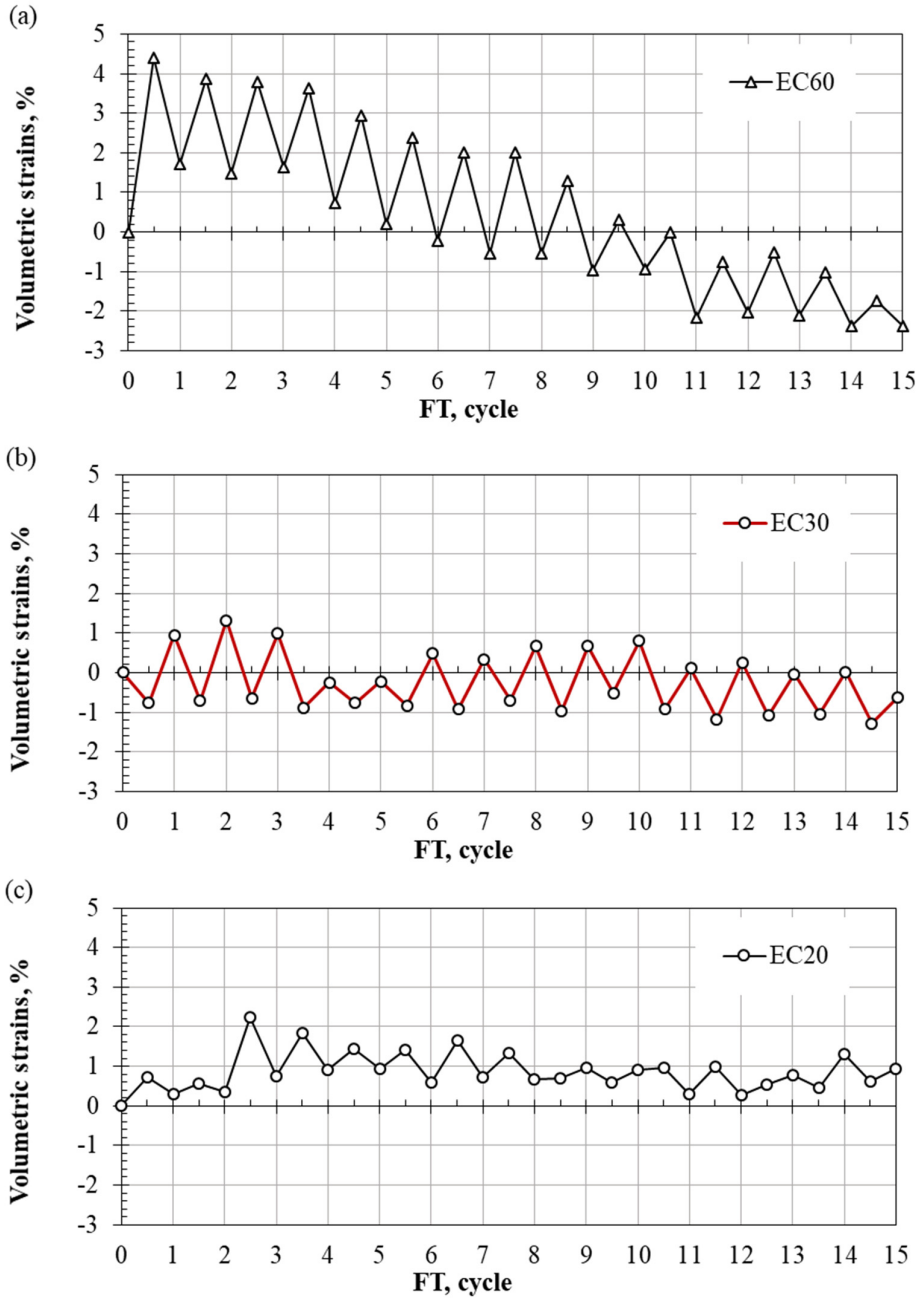


Figure 2. Volumetric strains induced during FT cycles for (**a**) EC60, (**b**) EC30, and (**c**) EC20.

Figure 5a–c presents the consolidation curves for 60%, 30%, and 20% clay content for clays before freezing and after 1, 5, 10, and 15 cycles. The compression index Cc is examined for the three clay contents, and it was found that 60% clay content at FT conditions increases compressibility in general for materials with excessive fines.

Examining Figure 6a: The compression index increased after the first cycle and then stabilized for all subsequent cycles, indicating an increase of 3 to 4 folds when comparing

the 60% fines to the 20% and 30% fines material. Figure 6b presents the swell index, which is found slightly decreasing with an increase in the number of cycles for the 60% and 30% fine content. The 20% clay content indicated small variations in all FT cycles.

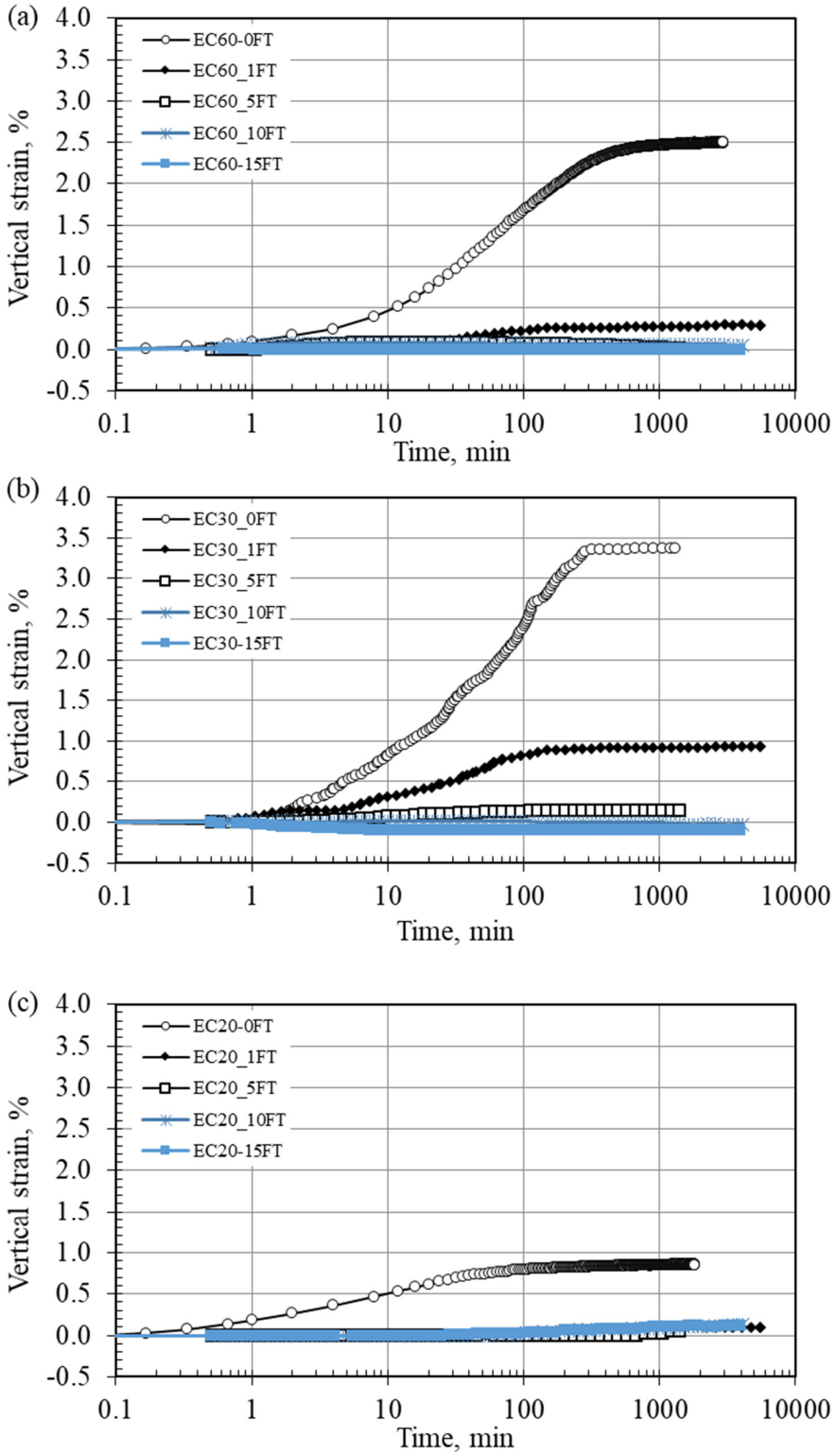


Figure 3. Swelling characteristics at different FT cycles for (**a**) EC60, (**b**) EC30, and (**c**) EC20.

The resulting settlement or swell in wet conditions may be too much for structures built on a cover liner with a high clay percentage. It is difficult to determine the maximum

limit that must be specified for clay content in relation to the vertical movement. This is mostly determined by the stresses expected to be applied to the surface of the cover liners.

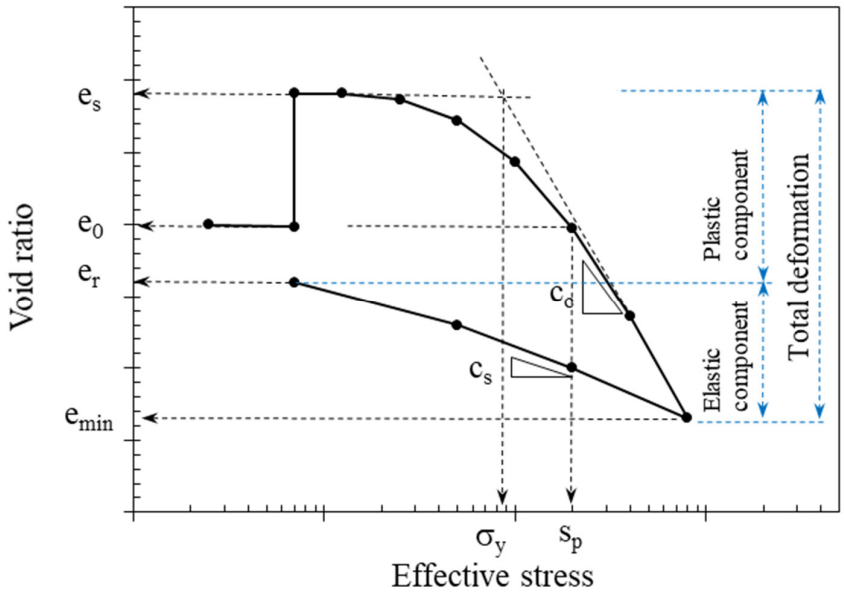


Figure 4. Typical consolidation curve with main characteristics.

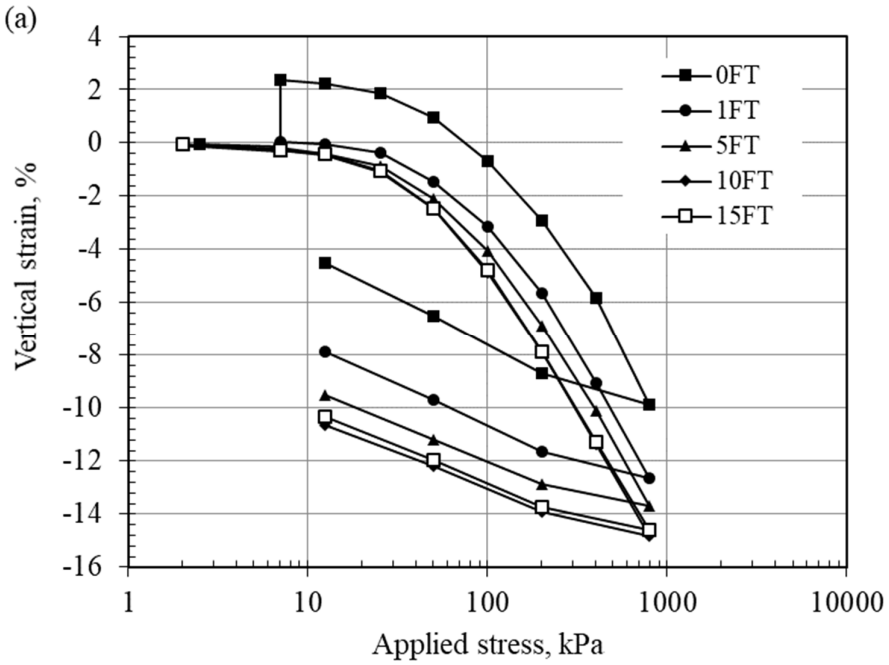


Figure 5. *Cont.*

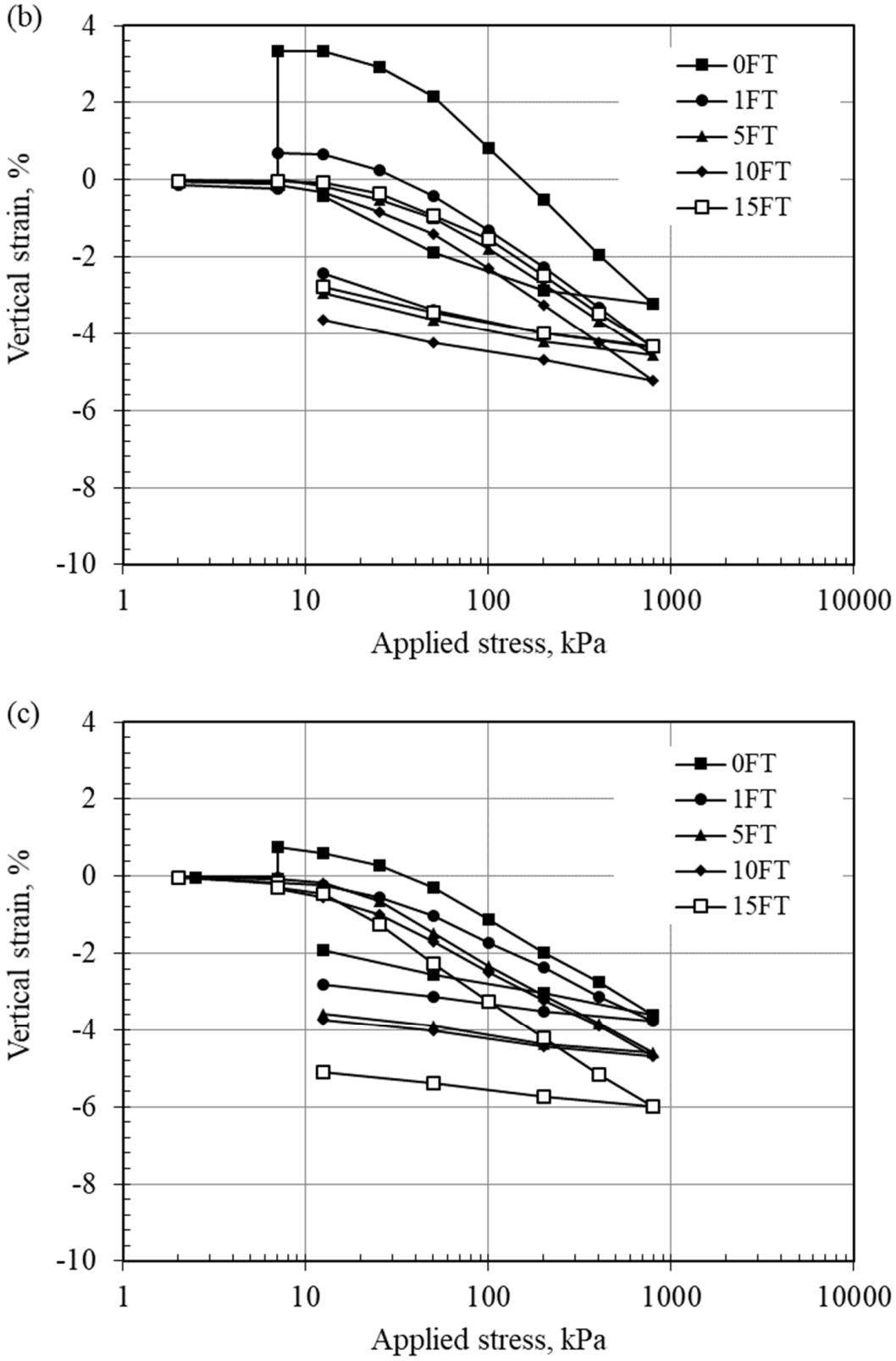


Figure 5. Consolidation curves for (**a**) EC60, (**b**) EC30, and (**c**) EC20.

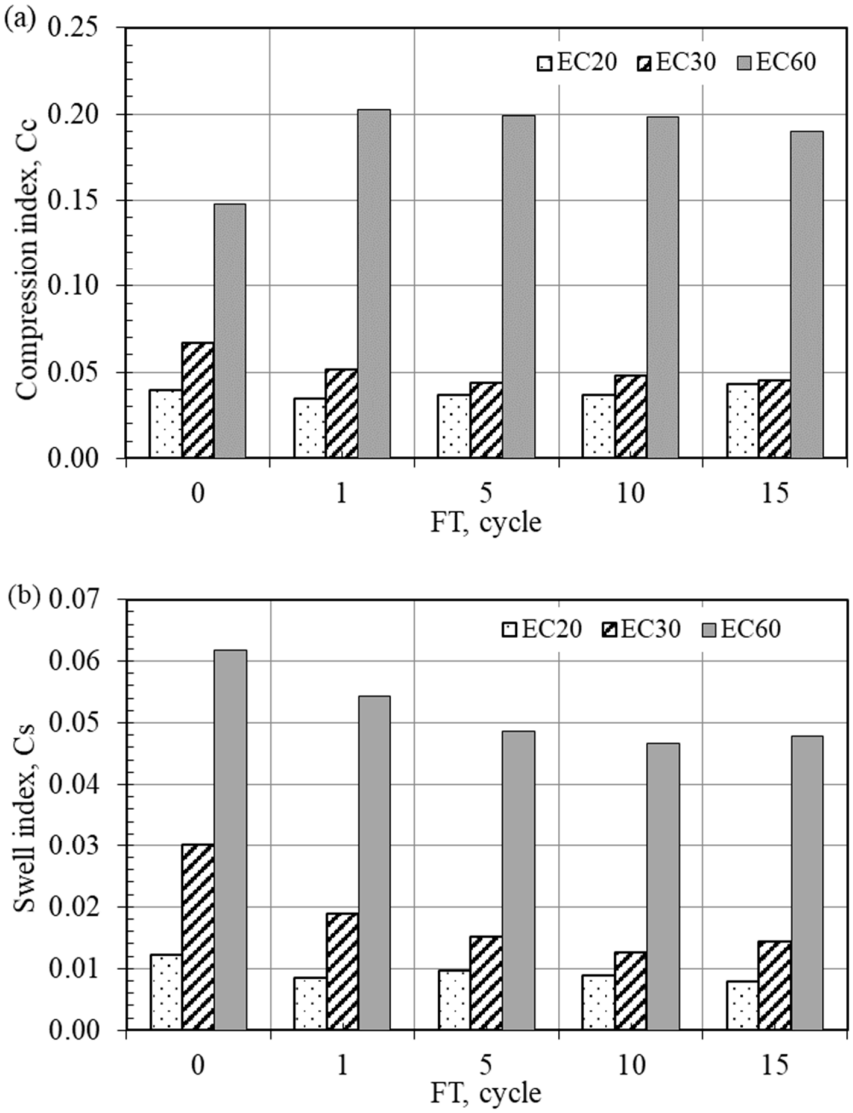


Figure 6. Variation of consolidation characteristics: (**a**) compression index and (**b**) swell index.

Accurate and sustainable design depends on the plastic deformation that external loads or environmental actions cause in the liner layers. According to Li and Selig [33], soil type and stress state have an impact on the substantial elastic and plastic deformation that occurs during the lifetime. Figure 7 presents the profile of the elastic and plastic deformation changes that are induced during different FT cycles (i.e., 0, 1, 5, 10, and 15). The elastic and plastic deformations were computed following 5, 10, and 15 cycles of freeze and thaw cycles. The plastic deformation increases with the increase in FT cycles with the 20% clay, indicating higher plastic deformation compared to the 30% and 60% clay content. This is attributed to the presence of montmorillonite and other expanding minerals; the interlayer spacing of montmorillonite clay decreases with freezing, as seen by X-ray diffraction [34,35]. The elastic deformation is found to decrease with the increase in the FT cycle number in wetting conditions. It can be noticed that the elastoplastic response of these liners has been affected by FT actions, and the 30% and 60% clay contents behave nearly similarly with regard to the influence of the freeze-thaw effect.

The yield stress (σ'_y) refers to the point at which further deformation begins after exceeding a pre-consolidation stress value (Figure 4). This value is determined graphically from a one-dimensional consolidation curve [36,37]. The yield stress defined here was used for the purpose of quantifying the possible effects of successive FT cycles on the mechanical

behavior of tested mixtures. The yield stress could also reflect the fabric-dependent effects as studied by Stoltz et al. [38] for lime-treated expansive soil. Figure 8 presented the yield stress following 5, 10, and 15 FT cycles and indicated a drop observed in the first cycles and nearly remained unchanged over all investigated cycles. The yield stress was found higher for the 60% clay and reduced with the reduction of the clay content. It was reported as small as 20 kPa for the 20% clay content. The above parameters can be used to compute settlements and vertical deformation changes under pressures applied by structures placed on clay-sand mixture layers or liners constructed for different purposes.

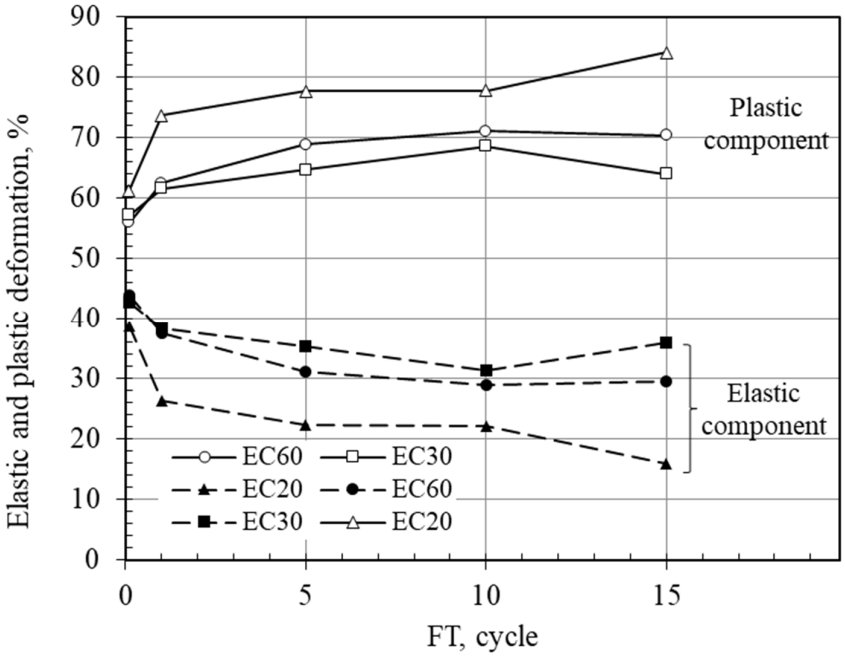


Figure 7. Development of elastic and plastic deformations with ascending FT cycles.

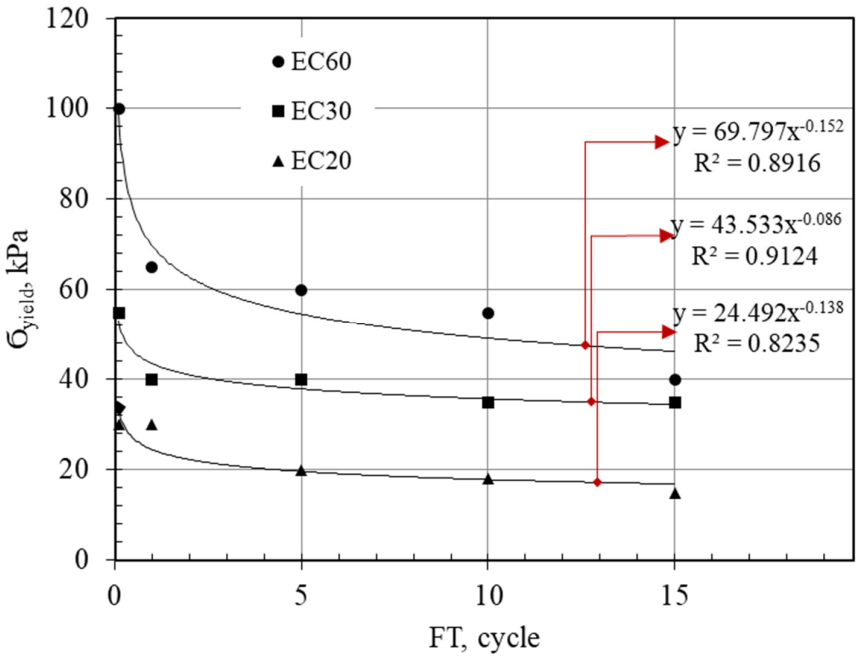


Figure 8. Variation of yield stress with ascending FT cycles.

4.3. Effect of FT Cycles on the Long-Term Performance of Hydraulic Conductivity for Liners

Figure 9a,b show how freeze-thaw cycles affect hydraulic conductivity. The values shown here were obtained from the continuous measurements using the falling head test as mentioned before. Because hydraulic conductivity is the primary regulating element, the sustainability of liner layers over time is of great significance. Hence, the long-term effect of FT must be evaluated and taken into account when the site is located in areas prone to periodic freeze and thaw. The observed permeability values before and after applying many FT cycles were presented throughout time (Figure 9a,b) for 20EC and 30EC liners, respectively. It can be seen that measurements are not stable for the first few days and that the hydraulic conductivity of liners subjected to freeze-thaw action is higher than in non-FT conditions in general. With more time, the measurement begins to stabilize. The migration of fines from soil pores causes an increase in hydraulic conductivity, and as a result, the collapse of large holes can occur following fine migration, causing a decrease in hydraulic conductivity. This pattern of increasing and decreasing hydraulic conductivity could be repeated until equilibrium was reached [27]. Measurements during the first 20 to 30 days are influenced by the movement of particles and water through the pores. Fines are lost during the earliest stages of soaking, which can result in unreliable hydraulic conductivity measurements.

It can be seen that the 30% clay content mixture tends to preserve the hydraulic conductivity close to the desired design value of 10^{-7} m/s; however, the 20% clay content mixture may not be successful when subjected to FT cycles. In places with frequent freeze-thaw cycles, it is recommended to consider a higher percentage of fines. The values acquired here are valid for the type and characteristics of the clay described, and the exact measurements must be checked for each clay to be used.

To summarize, the effect of freeze-thaw cycles on expansive clay-sand liners is complex and varies depending on the number of cycles, clay mineralogy, and liner composition. While certain materials exhibit higher hydraulic conductivity and structural alterations, Podgorney and Bennett [39] claimed that GCL liners show resilience to freeze-thaw effects across multiple cycles.

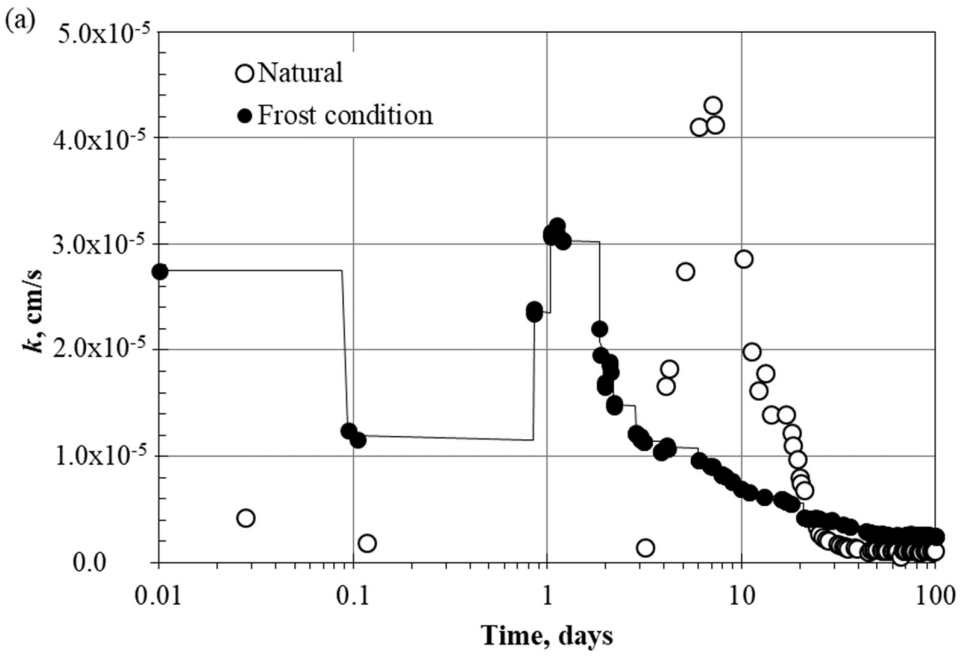


Figure 9. *Cont.*

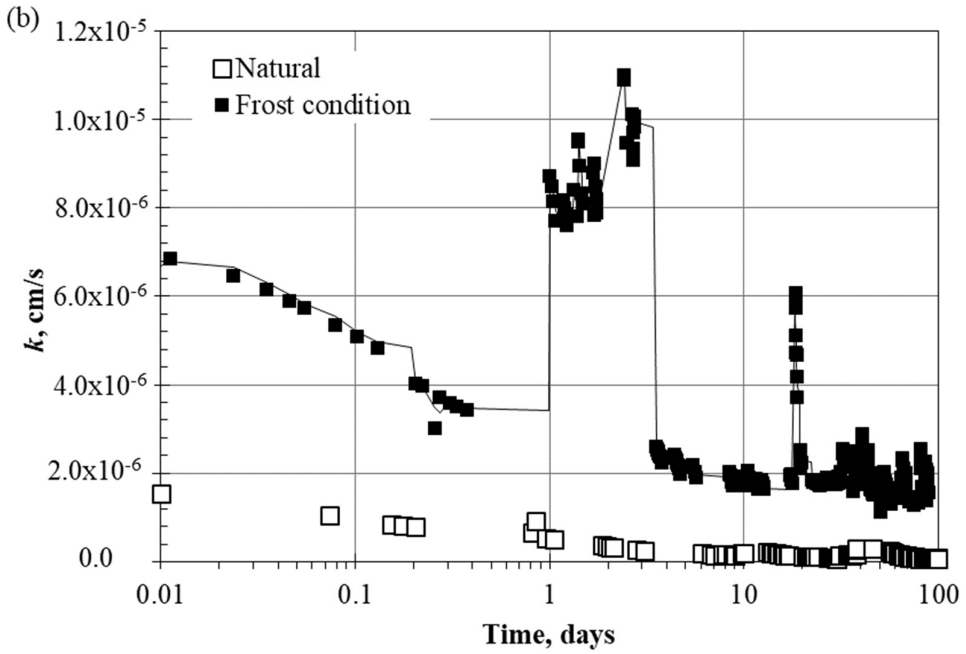


Figure 9. Effect of frost conditions on the stability of hydraulic conductivity for (**a**) 20EC and (**b**) 30EC.

5. Summary and Conclusions

This study investigated the hydromechanical behavior of natural liners made of clay with expansive minerals and sand under the effect of successive freeze-thaw cycles. Different contents were considered to cover a wide range of liner applications. The main findings could be stated as follows:

- The volumetric strains developed during subsequent FT cycles are significant and proportional to the kind and amount of expanding minerals (i.e., montmorillonite), and they reached a value of 4.5% for liners with a greater expansive soil content.
- After the initial FT cycle, vertical strains under wetting conditions were decreased by almost 90%; this indicates that soil structure has been extremely altered even for a single FT cycle.
- The increased clay content was shown to increase compressibility and induce undesirable vertical movement. The compressibility index appears to change within significant ranges, accompanied by a distinct shift in vertical strain.
- FT actions also alter the elastoplastic response of these liners; the plastic deformation component has been increased versus the reduction of the elastic component with the increase in FT cycles during consolidation.
- The compression index Cc for clay contents showed an increase of 3 to 4 folds for 60% clay content at FT circumstances, and that can cause excessive settlement. The swell index can also change, although it normally remains constant after the first few cycles. The yield stress was reduced by about 60% along with elevating FT cycles.
- The hydraulic conductivity during an extended period of 100 days shows dramatic changes and deterioration due to FT actions, structural changes associated with FT actions, and developed cracks as key factors in increasing hydraulic conductivity several folds.

When designing cover liners composed of expansive clay-sand mixtures, the freeze-thaw effect in places susceptible to seasonal environmental changes and harsh weather conditions must be considered. Highly plastic clays may take longer than 30 days to acquire stable laboratory values for hydraulic conductivity; the sustainability of liner layers over

time is of great significance. It is recommended that the fine content of clay-sand mixtures be increased to compensate for the effects of freeze and thaw. The outputs of this study provide an insightful view into the hydro-mechanical behavior of liners under freeze-thaw action for a wide range of expansive clay content and guide a sustainable design.

Future works, including in-depth investigation of micro-structural alteration induced by FT actions using MIP or SEM techniques, will assist in providing fast and reliable design approaches for accurate model designs.

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Conflicts of Interest: 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.

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