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Effect of freeze–thaw cycling on the mechanical properties of lime-stabilized expansive clays

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ABSTRACT

In cold regions, earth structures such as embankments and roads are exposed to periodic freeze–thaw (F–T). This study was conducted to investigate the impact of F–T cycles on the mechanical properties of two types of plastic soils, stabilized with lime. Two types of clayey soils (high plasticity—bentonite and low plasticity—kaolinite), both untreated and lime-treated (with a curing time of up to 300 days), were tested. Durability was assessed as the influence of F–T cycles on the unconfined compressive strength (UCS), direct shear strength, porosity and volume changes of these soils. The results indicate that the volume of the treated soils increased during the first F–T cycles, after which this increase became less pronounced. The UCS increased significantly when the curing time was extended from 3 to 28 and then to 300 days. After subjecting the materials to F–T action, the damage (crack formation) caused by the formation of ice lenses in the pores of lime-stabilized soil samples was found to have a more significant effect in bentonite soil than in kaolinite soil. Both direct shear strength parameters presented some alterations with the increased number of F–T cycles (the friction angle increased slightly and the cohesion decreased). The F–T effects on the direct shear strength were mainly reflected in cohesion, thus affecting the durability of the stabilized soil.

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1. Introduction and scientific background

In many cases, the quality of the materials available for civil engineering works needs to be improved. An established technique developed for reusing in situ non classified soils for construction work is to improve the soil properties. Such improvements are also motivated by economic and environmental reasons. The stabilization of clayey soils with hydrated lime, quicklime, cement or other binders leads to a material with improved mechanical and physical properties.

Quicklime, which is non-hydrated calcium oxide, absorbs water from the moist soil, thereby changing into calcium hydroxide that hardens the links between soil particles and improves the soil strength (NLA, 2004). The immediate reaction that takes place between lime and clay is cationic exchange between the ions associated with the surfaces of the particles and the calcium ions in the lime, leading to flocculation (Bell, 1996). This reaction is succeeded by a long-term one which can take months or years to complete, depending on the rate of chemical breakdown and the hydration of the silicates and aluminates in the clay. This reaction is known as the pozzolanic reaction and results in the formation of a cementitious material. A number of studies have been performed in order to analyze the behavior of lime-treated clays, but few have been carried out on the durability of the material, in particular the effect of freeze–thaw (F–T) cycles (Al-Kiki et al., 2011; Al-Mukhtar et al., 2012; Ingles and Metcalf, 1973; Locat et al., 1996). The behavior of clay materials under F–T cycles is a complex phenomenon as it depends on several parameters such as the type of clay mineral (kaolinite, illite or montmorillonite), their degree of saturation, the duration and the amplitude of the F–T cycles (Cui et al., 2014; Svensson and Hansen, 2010; Wang et al., 2007). The effect of the freeze may be irreversible for some materials that change texture completely or reversible as in the case of montmorillonite (Svensson and Hansen, 2010). Heller-Kallai (2013) showed that due to the effect of temperature, some minerals become amorphous, while others recrystallize to new phases. The applied gradient of temperature alters the structure and the properties of clay materials. The degree of saturation of the material itself plays an important role in this change (Birgersson et al., 2008).

In cold regions, the mechanical properties of soils are severely affected by the ice lenses created between particles during freezing and the excess of water during thawing (Konrad, 1989). These effects can substantially reduce the strength and bearing capacity of the foundation soil (Aldaood et al., 2014; Kamei et al., 2012; Wang et al., 2007). According to Lee et al. (1995) cohesive soils with a uniaxial compression strength (UCS) <55 kPa exhibit negligible freezing–thawing effects while soils with a UCS >103 kPa exhibit a decrease of more than 50% in resilient modulus due to the freezing–thawing process. Parsons and

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Milburn (2003) showed that weight loss in the soil samples ranged from 2 to 41% after 12 F–T cycles. Soil weight loss is induced by the soil-particle separation on a microscopical scale due to ice pressure within the soil pores. The volume change during the freezing of water increases the pressure within the soil porosities and reduces particle cohesion and soil strength, making the soil more erodible. Cement-treated soils experienced the least weight loss, with reductions in mass of 2 to 7%. Lime-treated samples had the greatest losses, particularly for lean clay. Fly ash-treated soils had intermediate losses that ranged from 7 to 19%. Wang et al. (2007) noted that by increasing the number of F–T cycles, there was a slight and continuous decline in the resilient modulus and the failure strength. For a soil under a constant confinement pressure, subjected to different numbers of F–T cycles, the failure strength decreased slightly at the beginning then increased to a certain level and remained constant without being influenced by the number of F–T cycles. The particle rearrangement caused by the applied pressures closed the cracks produced by the F–T action and improved the soil strength. Khoury and Zaman (2007) investigated the effect of freeze–thaw durability of aggregate stabilized with various additives, including cement kiln dust, fly ash and fluidized bed ash. Results showed that the resilient modulus (modulus of elasticity under cyclic loads) decreased as the number of F–T cycles increased. This behavior was attributed to the fact that pozzolanic reactions are prevented due to F–T cycles. Bin-Shafique et al. (2010) found that F–T cycling did not change the plasticity of fly ash stabilized soils. However, the unconfined compressive strength decreased by about 20% for stabilized soft soils and by about 40% for stabilized expansive soils. Even after losing strength due to F–T cycling, the strength of stabilized soils was still at least three times higher than that of the unstabilized soils. Al-Kiki et al. (2011) showed that natural clayey soil did not sustain the effects of environmental conditions, but that after stabilization with lime, the mechanical characteristics improved. Similar observations were documented by Aldaood et al. (2014).

In view of the lack of references reporting on the durability of lime treated clayey soils subjected to F–T cycles, this paper analyzes the behavior of two clays with two different plasticities: kaolinite and bentonite. These materials are studied in a non-saturated condition at the optimum water content. The objective of this research is to investigate the effect of the curing time and the percentage of lime treatment on frost resistance and swelling pressure. In addition, the intensity and the kinetics of degradation versus the number of F–T cycles were analyzed. Moreover, the porosity and the pore size distribution of some samples were investigated by a mercury porosimetry test in order to analyze the effect of lime treatment and F–T cycles.

2. Materials

2.1. Material properties

Two clayey soils were used in this study: a polwhite bentonite and a kaolinite. The composition of the materials was established using mineralogical analysis by X-ray diffraction and atomic emission spectroscopy. The results of these tests showed that the bentonite is composed of 85% smectite, 10% feldspaths and 5% cristobalite, and the kaolinite of 90% kaolinite and 9% muscovite (Table 1). Bentonite is a very plastic, expansive clay with a plasticity index (PI) = 162% while kaolinite has a lower plasticity index (PI = 27.3%).

Table 1
Composition plasticity and optimum water content of the studied soils.

Type of soil	Composition	Liquid limit [%]	Plasticity index [%]	w_{OPT} [%]	ρ_{OPT} [kN/m^3]
Bentonite	85% smectite 10% feldspaths 5% cristobalite	211	162	39.2	11.9
Kaolinite	90% kaolinite 9% muscovite	59	27	25.1	14.5

The quicklime used in this study, supplied by the French company LHOIST, is a very fine lime that passes through an 80 μm sieve. The activity of the lime used was 94% (Al-Mukhtar et al., 2010).

2.2. Sample preparation

The bentonite and the kaolinite soil samples were stabilized by using 5% and 3% lime respectively, representing the optimum lime contents based on the Eades and Grim method (1966). The soil–lime mixtures were first prepared by thoroughly mixing dry predetermined quantities of soil and lime. Then the required amount of water, corresponding to the optimum moisture content of natural soils, as shown in Table 1, was added and the samples were remixed to obtain a uniform moisture distribution. The mixture was then placed in plastic bags and left for 1 h. Following, the soil sample was statically compacted inside a cylindrical mold, until it reached the maximum dry unit weight of the natural soil (Table 1) with a final dimension of 50 mm in diameter and 100 mm in height to serve for the unconfined compression test. The compaction method was the ASTM (D-5102) standard test method for unconfined compressive strength of soil–lime mixtures. After compaction, the soil sample was immediately extracted from the mold and then wrapped with paraffin to prevent moisture loss. The samples were left to cure at room temperature (20 °C) for different curing durations (3, 28 and 300 days).

3. Experimental procedures

3.1. Freezing and thawing test procedure

At the end of each curing duration (3, 28 and 300 days), the stabilized soil samples were subjected to 0, 1, 2, 5 and 10 F–T cycles following the ASTM (D-560) test method for freezing and thawing of compacted soil–cement mixtures, using an F–T chamber. The soil samples wrapped in the paraffin film were placed in the F–T chamber (three dimensional closed system freezing) with a constant temperature of −23 °C for 24 h. After that, the soil samples were subjected to thawing at 21 °C for 23 h. The weight and volume of the soil samples were recorded at the end of each F–T cycle in order to ensure constant water content. Volume variations were recorded by measuring the height and diameter of the soil samples.

3.2. Unconfined compression and direct shear tests

The unconfined compressive strength (UCS) was determined according to the ASTM standard protocol (D-5102). The load was applied to the soil samples with a strain rate of 0.1 mm/min, using a hydraulic press (INSTRON 4485). The loading process continued until the failure of the samples occurred. The tests were conducted on cylindrical remolded and stabilized samples of 50 mm diameter and 100 mm height, cured for 3, 28 and 300 days respectively, and subjected to 0, 1, 2, 5 and 10 F–T cycles. Finally, the dimensions of the cylindrical samples subjected to F–T cycles were measured after each cycle in order to obtain the volumetric variation with respect to the initial dimensions.

The direct shear test was conducted on natural and cured (3 and 300 days) lime-stabilized samples (60 × 60 × 20 mm) of bentonite and kaolinite, subjected to 0, 1 and 5 F–T cycles. A conventional direct shear device was utilized, subjecting the samples to 100, 200 and 300 kPa normal stresses, in order to obtain the values of shear stresses and, in the end, the values of cohesion and friction angle. Note that the unconsolidated undrained (quick test) direct shear test was used in this study.

3.3. Swelling test

The free swell oedometer test method (ASTM D4545-95) was used to measure the swelling pressure on soil samples of 65 mm diameter and 10 mm height. The soil sample is brought into contact with water and allowed to swell freely in the oedometer cell. Then the soil is gradually consolidated back to its original volume using a hydraulic press (INSTRON 4400) with a static load (0.001 mm/min). The swelling pressure is defined as the stress necessary to consolidate the specimen back to its original volume (Sridharan et al., 1986).

3.4. Mercury intrusion porosimetry test

The pore size distribution was measured by mercury intrusion porosimetry (MIP) with an AutoPore IV apparatus ($P_{max} = 400$ MPa), allowing the investigation of pore radii ranging from 3.7 nm up to 1000 μm. By measuring the volume of mercury that intrudes into the sample with each pressure change, the volume of pores in the corresponding size class is calculated. A key assumption in MIP is the pore shape. The method assumes a cylindrical pore geometry using a modified Young–Laplace equation, generally referred to as the Washburn equation (Giesche, 2006). The samples for the MIP test were carefully trimmed into pieces having an approximately cubic shape and a volume of approximately 1 cm^3, and were vacuum dried by lyophilisation using a Freeze Dryer apparatus (ALPHA 1-2 Ld Plus—Martin Christ Gefriertrocknungsanlagen GmbH) in order to remove the pore water without damaging the original texture of the soil sample. MIP tests were conducted on the soil at the end of 28 days of curing at 20 °C and after the end of the 10th F–T cycle.

4. Results and discussion

4.1. The effect of lime content on the swelling pressure

Swelling pressure tests were conducted on soil samples stabilized with different lime contents and cured for 28 days at 20 °C. Fig. 1 shows that the results obtained confirm those proposed by Eades and Grim (1966). Initially, the untreated bentonite exhibited a swelling pressure of 995 kPa, whereas the untreated kaolinite presented a swelling pressure of 360 kPa, indicating that it is less active than bentonite. The swelling pressure became negligible at 3% of lime for kaolinite and 5% for bentonite (relative to the dry mass of soil), respectively.

4.2. The effect of F–T cycles on the unconfined compressive strength

Fig. 2 shows the variation in the UCS of the bentonite soil samples with curing times and number of F–T cycles. Results show, for the 0% of gypsum, a linear decrease in the UCS with F–T cycles; for the lime treated samples after 3 days a decrease in the UCS followed by a slight increase for the lime treated samples after 28 days and 300 days a linear decrease in the UCS with F–T cycles. Overall, the UCS of the lime stabilized bentonite decreased with the number of F–T cycles. Lime addition increased the UCS of the soil samples and as curing time increased, the UCS increased. The soil samples presented considerable gains in strength, achieving, after 300 days of curing, a 9 times higher UCS than in the untreated soil sample. These gains in strength are attributed to the pozzolanic reactions between lime and clay particles. Similar observations were reported by Al-Mukhtar et al. (2010, 2012).

The UCS of the untreated soil samples decreased with increasing number of F–T cycles. The reason for this reduction in UCS is that before freezing, the soil particles in the sample were lightly packed (Konrad, 1989). During freezing, ice lenses were formed, inducing a more dispersed packing and segregation of the soil particles.

The effect of F–T cycles on the UCS varied, depending on the initial curing time. This behavior of lime-stabilized bentonite can be attributed to the fact that as the reaction between lime and clay is a continuous one, the initial stages are not yet completed. This phenomenon is interrupted during freezing at −23 °C and reactivated during thawing at 20 °C, leading to an increase in mechanical strength. Comparing the results obtained during the F–T tests, and also observing the structure of the material, one can conclude that the cementation bonds created between bentonite particles are very strong; this gives the material a slightly brittle behavior (Fig. 3) which also has an influence on its durability (the UCS decreased with a higher number of F–T cycles compared to soil samples not subjected to F–T cycles). After 28 and 300 days of curing, the variation in the UCS as a function of the number of cycles was similar to that of untreated soils, namely an almost linear decrease with the increasing number of F–T cycles.

It is clear from Fig. 4 that kaolinite strength increases when the soil is stabilized (treated with lime), even though the UCS gains are not as pronounced as in the case of stabilized bentonite, proving that kaolinite is less reactive. In the untreated kaolinite, strength continues to decrease with F–T cycles. From the tests conducted on lime treated samples cured for 3 and 28 days, it can be concluded that there is a little difference in strength variation, meaning that stabilization is effective in the long-term. According to Bergaya and Lagaly (2006), clay mineral has a range of exchange capacities because of differences in structure and in chemical composition. The ranges (in milliequivalents per 100 g) for kaolinite are: 3–15 and for bentonite: 70–100. Therefore, the short-term reactions between the tested bentonite clay and lime are highly active. The UCS of the stabilized kaolinite was less influenced by the increased number of F–T cycles than the stabilized bentonite. As shown on Fig. 5, the treated kaolinite soil presented no visible changes (i.e. cracks) in texture and showed a good resistance against F–T cycles.

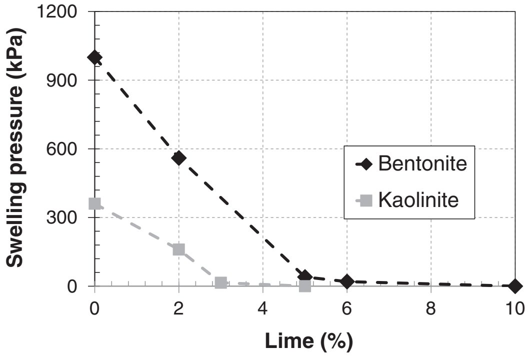

Fig. 1. Changes in swelling pressure of tested clays with lime stabilization.

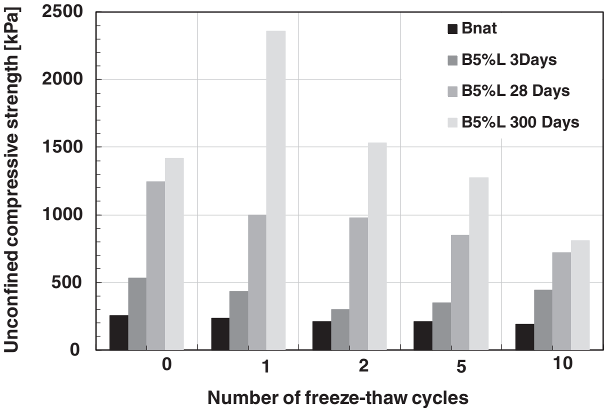

Fig. 2. The unconfined compressive strength of untreated bentonite (Bnat) and lime-treated bentonite subjected to freeze–thaw action.

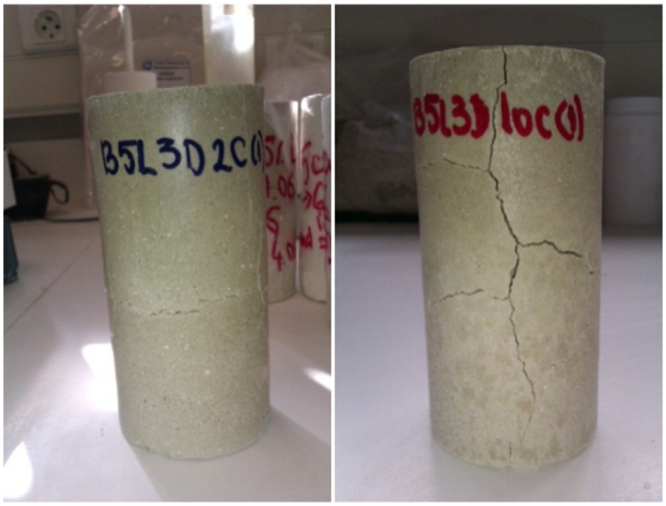

Fig. 3. Treated bentonite samples, cured for 3 days and subjected to 2 (left) and 10 (right) freeze–thaw cycles.

4.3. The effect of F–T cycles on the volume change

As previously mentioned, the F–T action was simulated in the laboratory on a series of cylindrical samples, both treated and untreated, protected with paraffin (closed system). Volume changes (Fig. 6) of the untreated kaolinite (Knat) and untreated bentonite (Bnat) continued to increase up to 10 F–T cycles. This behavior can be attributed to the increase in void ratio and the formation of cracks which induces an increase in hydraulic conductivity (Konrad, 1989). Moreover, at the beginning of tests, this sample showed low characteristic values of soil cohesion and friction angle, and displayed an increase in fissures and cracks with increasing F–T cycles. Wang et al. (2007) show that stabilization occurred after 10 cycles in their tested clay (fine-grained clay similar to our tested Knat). After 28 days of curing and one F–T cycle, it can be observed that there was a noticeable volume change in the stabilized kaolinite, which continued to increase until completion of the second cycle, after which it began to stabilize. The bentonite cured for 28 days presented a higher increase in volume in the first 2 cycles, after which the variations tended to stabilize (i.e. they become constant). In the case of untreated materials, the volume changes are caused by the formation of ice lenses in the structure of the material which induce cracks and decrease the strength during freezing. At the same time, during freezing, migration of water occurs from higher to lower temperatures as suction forms at the freezing front (Konrad and Shen, 1996). Therefore, during thawing, the water causes changes in the structure and the texture of the material. Fig. 6 also shows that after 300 days of curing, the samples increased in volume—even if this volume increase is the lowest, given the long period of curing and the development of the pozzolanic reaction which creates strong bonds between particles. The two materials behave differently: after stabilization, the volume changes decrease at a lower rate in the case of bentonite and at a higher rate in the case of kaolinite. The difference in volume change is small in treated kaolinite compared to that in treated bentonite. This can explain the UCS results.

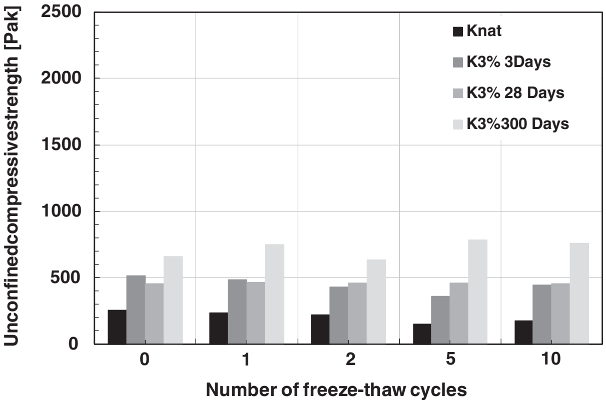

Fig. 4. The unconfined compressive strength of untreated kaolinite (Knat) and lime-stabilized subjected to freeze–thaw action.

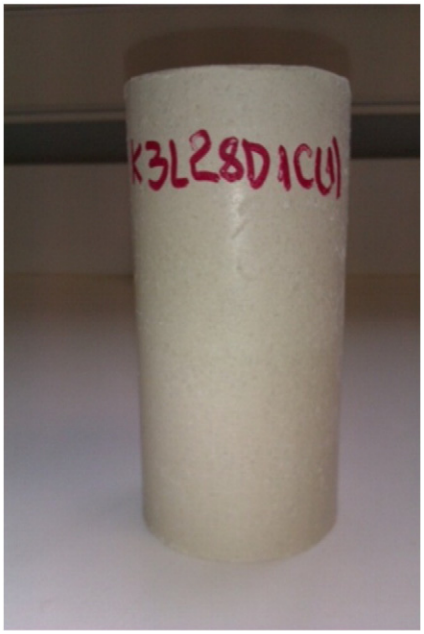

Fig. 5. Treated kaolinite sample, cured for 28 days and subjected to 1 freeze–thaw cycle.

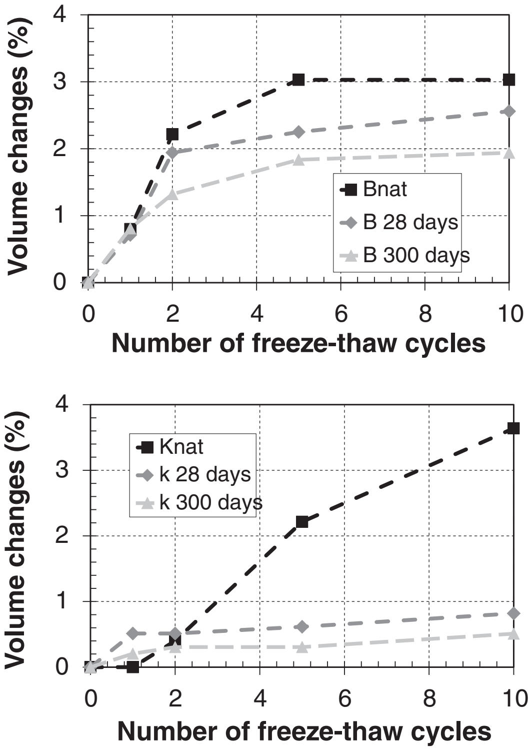

Fig. 6. The volume changes of lime-stabilized bentonite and kaolinite, cured for 28 and 300 days and subjected to freezing and thawing action.

Table 2
Undrained direct shear test results for lime-stabilized bentonite and kaolinite, with different curing times and subjected to 0, 1 and 5 freeze–thaw cycles.

Material	Curing time	Friction angle φ [°]			Cohesion c [kPa]		
		0 cycle	1 cycle	5 cycles	0 cycles	1 cycles	5 cycles
Bentonite	Untreated	27	27	26	116	109	90
	3 days	43	44	45	131	115	66
	300 days	62	64	66	447	341	111
Kaolinite	Untreated	21	22	23	101	95	81
	3 days	30	31	37	107	105	87
	300 days	42	47	46	150	116	95

4.4. The effect of F–T cycles on the shear strength

Results of the direct shear test conducted in a conventional apparatus are presented in Table 2 and Fig. 7. Comparing the results of direct shear parameters for the untreated and lime treated materials, the cohesion and the friction angle increased with the lime treatment for both materials. The cohesion of bentonite increased with curing time, reaching values almost 4 times higher after 300 days. For kaolinite, the lime treatment did not have such a distinct effect on the cohesion. The friction angle also increased with curing time, for both treated materials: the values are 1.4 times higher in the sample cured for 300 days than that of samples cured for 3 days. These results are in agreement with the UCS results and the increase in the shear strength parameters with curing time is related to the pozzolanic reactions between soil and lime.

During F–T cycles, the soil samples showed different variations in the shear strength parameters. For untreated soil samples, friction angle values remained almost constant, while there was a continuous reduction in cohesion for both soils. For the stabilized materials, the friction angle values changed slightly with the number of F–T cycles applied. This means that changes in the friction angle are similar in the two soils and can be considered to remain almost constant with increasing number of F–T cycles. In the case of the stabilized kaolinite and bentonite cured during 3 days, cohesion was reduced by half in the bentonite after 5 F–T cycles and by almost 20% in the kaolinite. The same behavior was observed for these two soils cured for 300 days: the cohesion of bentonite was reduced by 75% and by 60% for kaolinite after 5 F–T cycles. These results are in agreement with the UCS results. For the untreated soils, if we compare the ratio of UCS by cohesion, it can be noted in Fig. 6 that this ratio changes slightly in the bentonite (2.2 to 2.3) and highly in the kaolinite (2.5 to 1.8) with increasing F–T cycles.

The mechanism of shear strength variations during F–T cycling is attributed to the fact that before freezing, the soil samples can be assumed to be tightly packed and have a high shear strength. During freezing and the development of ice lenses, a dispersed packing is formed in which the soil particles are separated from adjacent particles by ice. On thawing, this dispersed packing subsists and weak shear zones develop along these ice lenses. Thus, lower shear strength values are reached as the number of voids increases. In addition, the direct shear strength of soil samples is affected by increasing F–T cycles. Results showed a significant decrease in shear strength for soil samples with these cycles. The

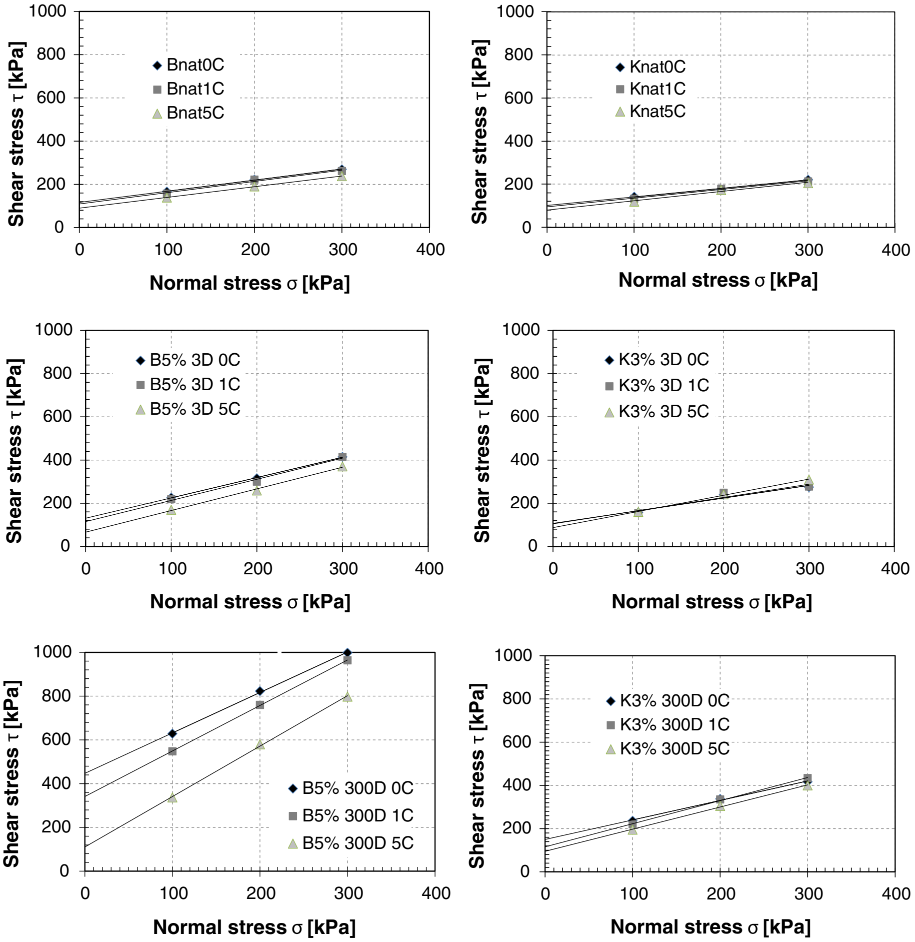

Fig. 7. Shear stress vs. normal stress for bentonite (on the left) and kaolinite (on the right) of untreated and lime stabilized soil at 3 days and 300 days (D on the figures) subjected to different freeze–thaw cycles (C on the figures).

changes were more pronounced during the fifth F–T cycles. The main mechanism governing the alteration of soil behavior caused by repeated freezing and thawing appears to be changes in the soil structure. The modification of the fabric is progressive, requiring several cycles (Van Vliet-Lanöe and Dupas, 1991). In the present study, the soil samples were subjected to 5 F–T cycles. However, the main changes in the shear strength are also attributed to the rearrangement of soil particles, which is confirmed by the mercury porosimetry test. Finally, the shear strength parameters of soil samples are directly influenced by the time of curing and the number of F–T cycles. The curing time increases the shear strength by increasing cohesion, whereas the F–T action reduces the cohesion, weakening the material.

4.5. The effect of F–T cycles on the soil fabric: pore size distribution

Fig. 8 shows the pore size distribution of cured and F–T cycled samples for both soils after 28 days of curing at 20 °C and after the end of the 10th F–T cycle.

Comparing the results of the two stabilized materials, the main observation is that the pore size distribution changes with F–T cycles: the proportion of large diameter pores increases in comparison to pores with small diameters in the two soils tested. The measured total pore volume is lower in kaolinite than in bentonite and so the amount of water absorption is lower in kaolinite than in bentonite. These results indicate that a connection exists between the increased volume of larger pores caused by F–T action (weakened material) and the lower values of the shear strength measured after repeated F–T cycles.

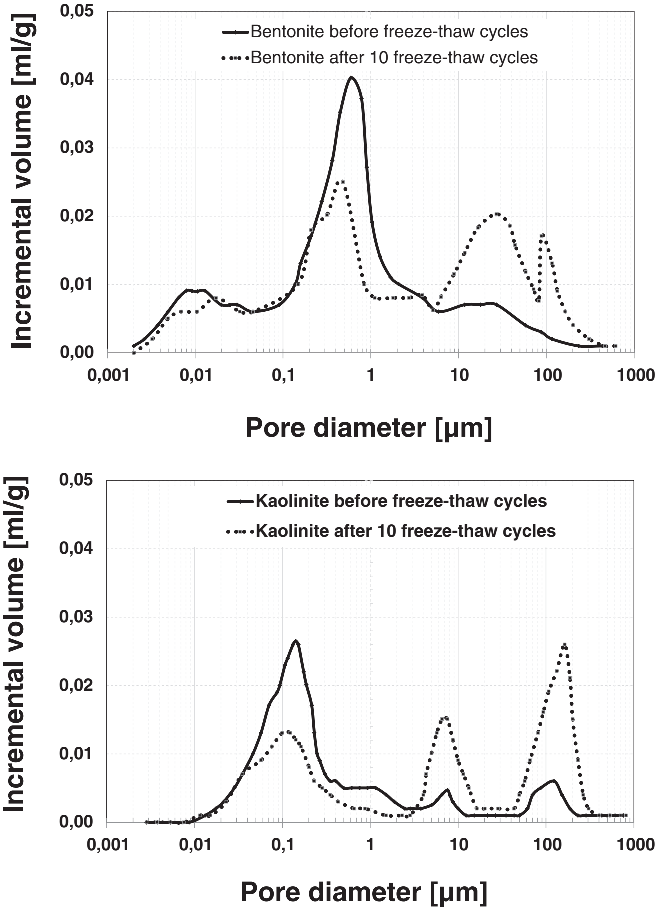

Fig. 8. Effect of the freeze–thaw cycles on the pore size distribution of the stabilized clays (28 days curing time).

5. Conclusions

In this research, a parametric study was carried out to investigate the effect of the curing time, the percent of lime added and F–T action on frost resistance and swelling pressure. The conclusions, which can be drawn from the laboratory tests, are:

1. Lime addition has a strong influence on the plastic and swelling properties of these two soils. The swelling pressure was eliminated in the case of bentonite with the addition of 5% quicklime, and of 3% quicklime in the case of kaolinite.
2. Lime addition improves the UCS of clayey soils, whether subjected to F–T cycles or not, as compared to the untreated soils. However, for the lime-stabilized bentonite cured for 28 days, the UCS decreased by 40% after 10 F–T cycles but was still higher than the UCS of the untreated material. In the case of lime-stabilized kaolinite, no significant losses in strength were observed, only slight decreases in samples cured for short periods—yet, compared to bentonite, the kaolinite does not gain as much strength. These behaviors can be explained by the kinetics of the lime treatment reactions which depends on the different mineralogical and crystallographic nature of the two clayey soils tested. The fast cation exchange reaction immediately consumes added lime in the smectite soil and not the kaolinite. The effectiveness of lime treatment in the long-term is determined by the reactivity of the pozzolanic reaction and the different amounts of lime that are not consumed by the different types of clay mineral in the short-term. Whatever the mineralogical composition of the clay soil, treatment with lime in the presence of water induces the formation of Ca-hydrates composed of different proportions of Ca, Si, and Al, resulting from the destruction of clay minerals (Al-Mukhtar et al., 2014). The improvement measured in the mechanical properties of the two tested soils depends on these reactions.
3. The bentonite soil presents higher volume changes than kaolinite soil, even after lime-stabilization. In the case of untreated and 28 days cured materials, the volume increases with the number of F–T cycles. Changes in the pore size distribution towards higher pore diameters play an important role in these volume changes when samples are subjected to F–T cycles. When the stabilized clay is cured for a longer period of time (300 days in this case), the volume changes are smaller.
4. F–T cycles affect the shear strength parameters of the soil samples. After 5 F–T cycles, a loss of approximately 37% and 75% in cohesion occurred in the stabilized kaolinite and bentonite respectively, for a curing time of 300 days. Even if the strength properties of clays are improved through stabilization, when subjected to F–T action these properties are strongly affected. The effects of F–T cycles on the direct shear strength are mainly reflected in the cohesion, while the frictional component of the shear strength did not vary significantly.

The laboratory experiments carried out assume that a curing of 28 days at 20 °C and UCS strength is considered as the basis for the assessment before F–T tests. The experimental conditions applied can be considered as the worst conditions faced in-situ for these soils: partial achievement of the reaction between lime and clay after 28 days and accelerated F–T cycles. Therefore, the transfer of the test results to construction works in the field involves the following recommendations concerning the lime treatment protocol before the freezing period. It is recommended to treat the soils with lime outside the freezing period and to apply watering in the field after lime stabilization in order to prevent strength losses and to enhance lime–clay interactions. Finally, lime treatment improves the behavior of clayey soils against freezing–thawing, but in construction projects it is important to consider a longer curing time for kaolinite soils than for bentonite soils before the arrival of these environmental conditions (F–T) on the treated soils.

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