



The influence of freeze–thaw cycles on the unconfined compressive strength of fiber-reinforced clay

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ABSTRACT

Freeze–thaw cycling is a weathering process that frequently occurs in cold climates. In the freeze state, thermodynamic conditions at temperatures just below 0 °C result in the translocation of water and ice. Consequently, the engineering properties of soils such as permeability, water content, stress–strain behavior, failure strength, elastic modulus, cohesion, and friction angle may be changed. Former studies have been focused on changes in physical and mechanical properties of soil due to freeze–thaw cycles. In this paper, the effect of freeze–thaw cycles on the compressive strength of fiber-reinforced clay is investigated. For this purpose, kaolinite clay reinforced by steel and polypropylene fibers is compacted in a laboratory and exposed to a maximum of 10 closed-system freezing and thawing cycles. The unconfined compressive strength of reinforced and unreinforced specimens is then determined. The results of the study show that for the soil investigated, the increase in the number of freeze–thaw cycles results in the decrease of unconfined compressive strength of clay samples by 20–25%. Moreover, inclusion of fiber in clay samples increases the unconfined compressive strength of soil and decreases the frost heave. Furthermore, the results of the study indicate that fiber addition does not decrease the soil strength against freeze–thaw cycles. Moreover, the study shows that the addition of 3% polypropylene fibers results in the increase of unconfined compressive strength of the soil before and after applying freeze–thaw cycles by 60% to 160% and decrease of frost heave by 70%.

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1. Introduction

In cold climates, soil is exposed to freeze–thaw cycles which are important in cold region engineering. The occurrence of freeze–thaw cycles in fine-grained soils results in changes in volume, strength, compressibility, densification, unfrozen water content, bearing capacity and microstructure. In the permafrost regions like Canada, it was found that the embankment constructed on the soil that had never experienced freeze–thaw cycles was damaged during just one year due to the loss of bearing capacity (Leroueil et al., 1991). It was also found that newly constructed highway embankments that had been left ungraded for a few years were damaged due to freeze–thaw cycles (Eigenbrod, 1996).

Qi et al. (2006) reviewed the last efforts made to investigate the influence of freeze–thaw cycles on soil properties. They summarized such influences on physical and mechanical properties. The former involves, for example density and hydraulic permeability. The latter refers to, for instance, ultimate strength, stress–strain behavior, and resilient modulus of soils. According to this research, loose soils tend

to be densified and dense soils become looser after freeze–thaw cycles. In addition, both loose and dense soils may retain the same void ratio after a number of cycles (Konrad, 1989). The large pores left after the thaw of ice crystals increase the soil permeability (Chamberlain et al., 1990). These cycles reduce the ultimate strength of soils. All over-consolidated soils exhibit a peak on the triaxial stress–strain curve and this peak is reduced or may even disappear (Graham and Au, 1985). Resilient modulus, an important factor in pavement designs, is decreased significantly by even a small number of freeze–thaw cycles (Simonsen and Isacsson, 2001). Moreover, these cycles decrease the undrained shear strength of fine grained soil (Graham and Au, 1985).

All above mentioned research work deals with unreinforced soil. To the best knowledge of the authors, the influence of freeze–thaw cycles on the strength of fiber-reinforced clay has not been investigated. The main purpose of this study is to explore the effect of freeze–thaw cycles on the unconfined strength of a clayey soil reinforced with steel (ST) and polypropylene (PP) fibers.

To improve the load carrying capacity of soils, several methods are available. One of the common methods is to mix randomly oriented fibers with soil mass. The primary advantage of randomly distributed fibers is the absence of potential planes of weakness that can develop parallel to oriented reinforcement (Maher and Gray, 1990). Many investigators have conducted triaxial, unconfined compression

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strength, CBR, direct shear, tensile, and flexural strength tests on specimens reinforced with paper, metal, nylon, and polyester fibers. Kumar et al. (2006) found that a significant increase in the unconfined compressive strength is achieved by inclusion of polyester fibers to highly compressible clay. They found that an increase in the strength of about 50–68% is reached by inclusion of 0.5–2% of 3 mm size fibers. The increase was 70–115% in the case of 6 mm (plain and crimped) and 12 mm fibers. The strength is augmented by increasing the percentage of fibers. These results are well comparable to those found by Tang et al. (2006). Tang et al. (2006) reinforced kaolinite soil with polypropylene fibers and observed an increase in the unconfined compressive strength. Steel fibers can also improve the soil strength but this improvement is not compared with the case of using other types of fibers (Gray and Ohashi, 1983; Gray and Al-Refeai, 1986).

2. Materials

In this study, a kaolinite clay soil is selected for conducting experimental tests, since fine-grained soils are more susceptible to freeze–thaw cycles. The clay is classified as MH in the Unified Soil Classification System. The details of the clay are presented in Table 1. The grain size distribution is illustrated in Fig. 1.

The compacted samples for unconfined compression tests are prepared using the standard Proctor compaction test. The soil has a maximum dry mass density of approximately 1.55 g/cm^3 with optimum moisture content (OMC) of approximately 39%. In order to inspect the purity of the soil, two XRD and XRF tests are performed on the specimens. These tests showed that more than 85% of the clay is kaolinite. The initial water content of the soil is in the range of 1–2% and thus, according to ASTM D-2216, the soil is considered completely dry in the tests. The specimens are reinforced with ST and PP fibers using 1, 2 and 3% fiber contents of weight of dry soil. The properties of the fibers are presented in Table 2.

3. Testing procedure

The scope of the present investigation is to study the effect of adding polypropylene and steel fibers on the strength characteristics of highly compressible clay soil compacted at 95% maximum dry density and exposed to 0–10 cycles of freeze–thaw. For each fiber content percentage, 5 specimens are prepared and subjected to 0, 1, 3, 5, and 10 freeze–thaw cycles. Some verification tests are also carried out in order to examine the repeatability of the experiment results.

3.1. Specimen preparation

All prepared specimens are cylinder-shaped with 38.5 mm diameter and 77 mm height. A moisture content of 27% is chosen in specimen preparation, since the sample compaction is very difficult at lower moisture contents. At moisture contents greater than 27%, polypropylene fibers absorbed most of the mixture water and adhere to each other. Therefore, a uniform fiber–clay mixture will not be obtained. To prepare the steel reinforced specimens, wet clay and steel fibers are mixed easily. The mixture is divided into four parts. Each part is poured in the mold and is compacted. This procedure is repeated to obtain a fully compacted sample.

Table 1
Soil properties.

G_s	2.61 (g/cm^3)
Plastic limit	40.6%
Liquid limit	69.4%
Plasticity index	28.8%

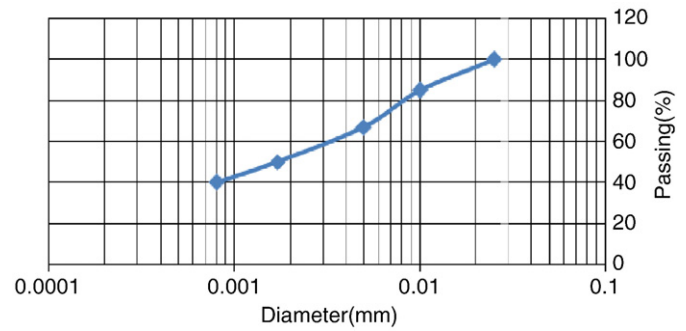


Fig. 1. Grain size distribution for clay.

The preparation of polypropylene reinforced samples is difficult. Three mixing methods are examined. In the first method, the clay is mixed with water and then polypropylene fibers are added. However, it is too difficult to compact this mixture. In the second method, the clay is mixed with fibers and then the water is added. This mixture is not homogenous and the most of water is absorbed by the fibers. In the third method, half of the dry clay and half of water are mixed prior to adding fibers. The fibers are not added to the clay–water mixture at this stage, since the fibers will adhere to each other if they are added. The remaining half of the soil, half of the water and all fibers are added to the clay–water mixture prepared in the previous step. The mixture of clay–water–fibers is then mixed gently. This procedure is found to be the best method to have homogeneous samples. The clay–water–fiber mixture is then poured in the mold in four layers and each layer is compacted before pouring the next layer. This procedure is repeated to prepare compacted homogeneous samples for unconfined compression tests. It should be noted that before the sample compaction start, the inside of the mold is coated with a lubricant in order to minimize the friction between the mold and the sample. As a result, no fracture occurs in the sample during removal. After the removal of each sample from the mold, the sample is immediately covered with a plastic layer to protect it from water evaporation.

It is also necessary to note that when a mixture layer is compacted, a nail is used to make the layer surface rough cautiously. This provides a reasonable bond between the subsequent layer and the previous compacted layer.

For freezing and thawing phases, specimens are placed in a refrigerator at -20°C for 6 h and then at $+25^\circ\text{C}$ for thawing phase for 6 h. These temperatures are the ones used in some previous researches, such as the study carried out by Qi et al. (2004). 6 h is a proportional period after which, the alteration of specimens height would become constant.

3.2. Unconfined compressive strength test

The strength of the specimens is measured using the unconfined compressive test apparatus according to the methodology described in ASTM D5311-92. The strain rate is kept constant at 1.2 mm per minute throughout the testing procedure.

Table 2
Fiber properties.

Steel fibers		Poly propylene fibers	
Length	20 mm	Length	12 mm
Diameter	1 mm	Diameter	0.1 mm
Unit weight	7850 kg/m^3	Unit weight	900 kg/m^3

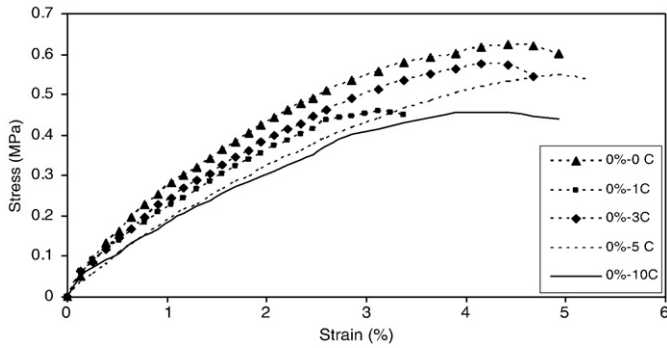


Fig. 2. Stress–strain variation of unreinforced samples.

4. Results

4.1. Unreinforced samples

As mentioned before, several unreinforced soil samples are tested to compare the behavior under freeze–thaw cycles with those of reinforced samples. Fig. 2 shows the variation of applied pressure versus the strain of unreinforced samples subjected to 0, 1, 3, 5, and 10 freeze–thaw cycles. In all figures, characters SF, PF, and NC stand for steel fiber, polypropylene fiber, and the number of freeze–thaw cycle, respectively. As shown in Fig. 2, the unconfined strength of the soil decreases by increasing the number of freeze–thaw cycles. The highest strength reduction is about 25% that occurs after the 10th cycle.

During freeze–thaw cycles, the heights of the specimens are measured several times. Fig. 3 shows the variation of unreinforced sample height during freeze–thaw cycles. In this figure, ΔH represents the height change for every freeze–thaw cycle and H is the initial height of the samples. When environment temperature drops below 0 °C, the soil moisture starts to freeze. As a result, ice crystals are formed in a freeze procedure and the sample is subjected to volumetric change. The crystal volume would increase up to 9 times and applies a considerable stress on soil aggregates, resulting in the change of soil characteristic in micro and macro scales. These findings well agree with those reported by Konrad (1989). A common influence of freeze–thaw cycles on soil is the frost heave. When samples are frozen, their heights increase and then, in the thawing phase, these heights decrease. However, the decrease and increase values are not the same and the specimens will not reach their initial height.

Fig. 4 illustrates the variation of the unit weight for unreinforced samples after freeze–thaw cycles. In this figure, γ_0 is the initial unit weight and γ_N is the unit weight after N cycles. As shown in Fig. 4, the unit weight of unreinforced samples is decreased by increasing the number of freeze–thaw cycles. This is a result of height increase in the samples whose weights are rather constant in freeze–thaw cycles.

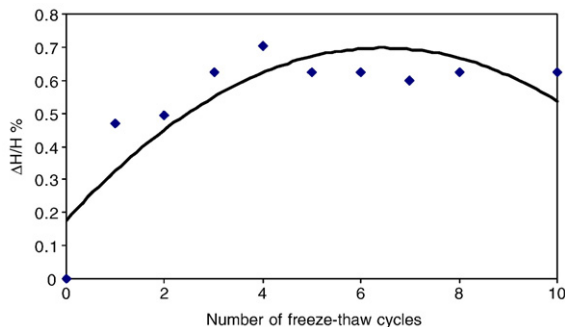


Fig. 3. Variation of height for unreinforced sample during freeze–thaw cycles.

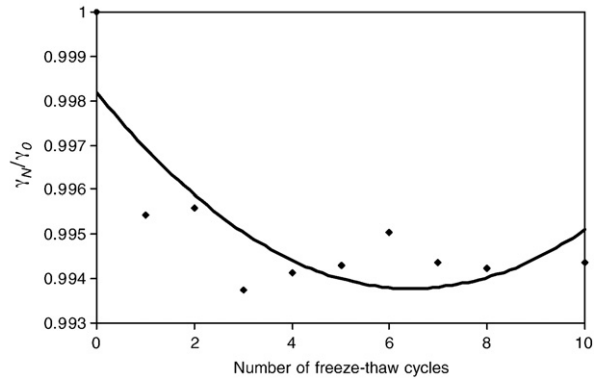


Fig. 4. Variation of unit weight for unreinforced sample versus freeze–thaw cycles.

4.2. Samples reinforced by polypropylene fibers

Fig. 5 represents the stress–strain variation for PF reinforced samples before applying freeze–thaw cycles and Fig. 6 represents the same results for PF reinforced samples after applying freeze–thaw cycles.

Figs. 5 and 6 show that adding 3% of poly propylene fibers increases the unconfined compression strength of clayey samples by 160% and 60% before and after applying freeze–thaw cycles, respectively.

Fig. 7 shows the compression strength ratio of polypropylene fiber-reinforced samples versus the number of freeze–thaw cycles for various fiber percentages. This ratio is defined as the strength of a reinforced sample at a given cycle divided by that of a same sample which is not reinforced and is subjected to the same cycle. These strengths are denoted by q_{u-N} and q_{u-0} respectively. It is obvious from Fig. 7 that polypropylene fibers do not significantly affect the strength reduction caused by freeze–thaw cycles. As it can be seen, the unconfined compression strength of samples decreases by 20–25% due to the application of 10 freeze–thaw cycles.

Fig. 8 shows the height variation due to freeze–thaw cycles for the sample reinforced by PF. As it can be seen, PF reinforcement reduces the sample height. The addition of 1–2% polypropylene fibers to the samples augments the increase of sample height to some extent. Whereas, adding 3% fiber content to the clay samples reduces the height increase by 70% compared with those of unreinforced sample and this is a significant change. Furthermore, by increasing the number of freeze–thaw cycles to 5–7 cycles, the height of the sample increases. Beyond this range, the height remains almost constant. This trend is also observed in the previous studies carried out on unreinforced specimens, where freeze–thaw cycles increased the height of specimens up to the 7th cycle (Wang et al., 2007).

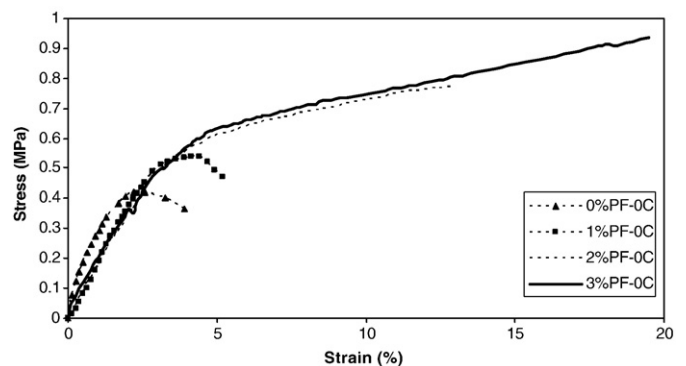


Fig. 5. Stress–strain variation for poly propylene fiber-reinforced samples after 10 freeze–thaw cycle.

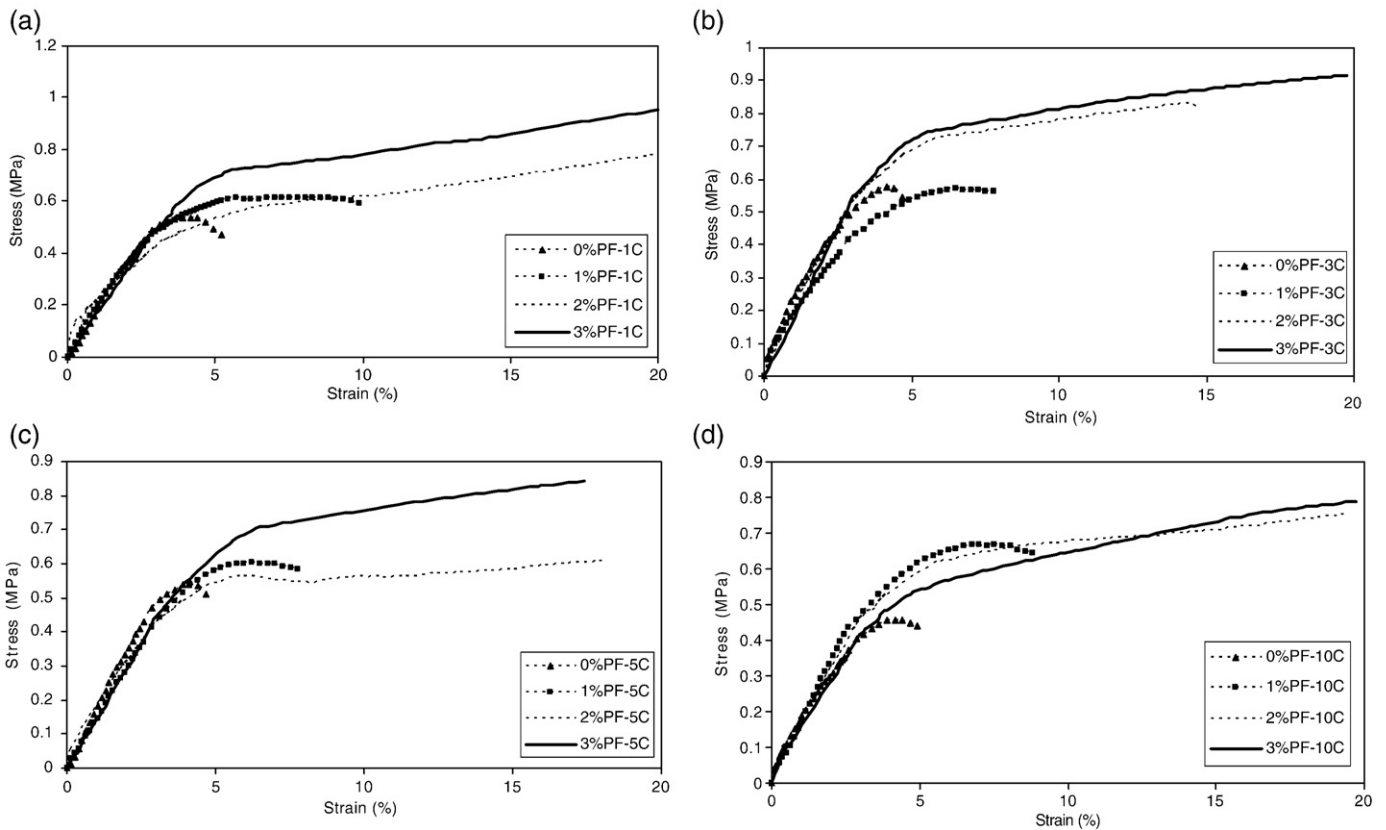


Fig. 6. Stress–strain variation for poly propylene fiber-reinforced samples after (a) 1 cycle, (b) 3 cycles, (c) 5 cycles, and (d) 10 cycles of freeze–thaw.

4.3. Samples reinforced by steel fibers

Figs. 9 and 10 represent the stress–strain variation for steel fiber-reinforced samples before and after the application of freeze–thaw cycles respectively. Fig. 11 shows the compression strength changes for steel fiber-reinforced samples after freeze–thaw cycles for various fiber percentages. From these figures, it is clear that the addition of steel fibers can increase the ultimate compression strength of soil by about 7% before applying freeze–thaw cycles and 6% after applying freeze–thaw cycles. In fact, by increasing the number of the cycles, the compression strength of reinforced samples is more decreased. During all of the cycles, the reinforced samples containing 2–3% of steel fibers have the greatest strength. This means that even for the reinforced sample, where steel fibers are added, the freeze–thaw cycles still have an effect, i.e. the strength reduction is still observable. The strength of all reinforced and unreinforced samples are reduced by about 20–25%

after applying 10 cycles (Fig. 11). This result has been also observed in the previous studies in which freeze–thaw cycles decreased the strength of soils subjected to 3–7 cycles (Wang et al., 2007).

The variation of height change in steel fiber-reinforced samples shows that an inclusion of 1–2% steel fibers does not affect the frost heave. However, adding 3% of fibers to the sample reduce the frost heave by about 20% (Fig. 12). This phenomenon is the result of low adhesion between the soil and steel fibers. By increasing the SF content beyond 3%, the soil height change decreases.

4.4. Comparison between steel fibers and polypropylene fibers

Based on the results presented in the Sections 4.2 and 4.3, it can be concluded that polypropylene fibers provide more strength and flexibility for reinforced samples than steel fibers do. It is noted that in the current study, it is not reasonable to quantitatively compare the variation of unconfined compression strength of steel reinforced

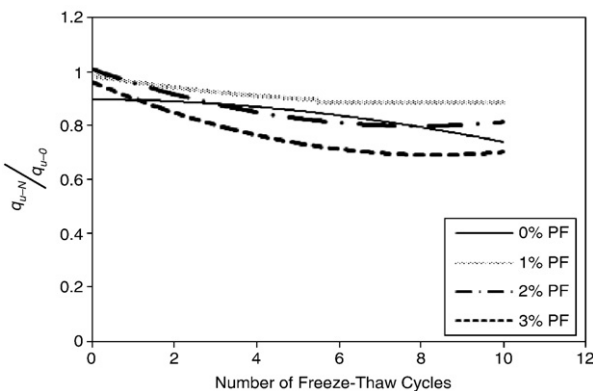


Fig. 7. Ultimate strength ratio for poly propylene fiber-reinforced samples.

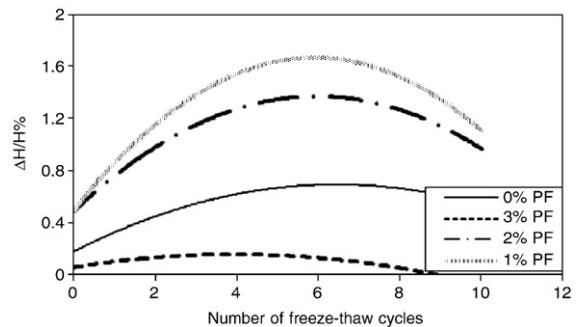


Fig. 8. Height changes for poly propylene fiber-reinforced clayey samples due to freeze–thaw cycles (ΔH = height change; H = initial height).

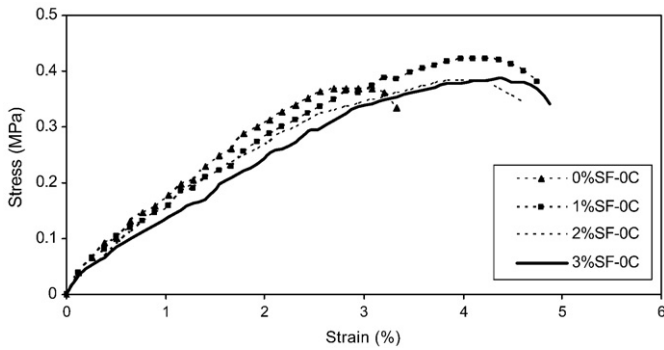


Fig. 9. Stress–strain variation for steel fiber-reinforced samples before freeze–thaw cycles.

samples with those of samples reinforced by polypropylene. These two fibers are used in the same percentage by weight of dry soil and they do not have equal unit weights. Consequently, the comparison is just made between height changes of the two groups of reinforced specimens.

Fig. 13 shows comparison between the height variation of samples reinforced with 1%–3% fiber contents of polypropylene and steel fibers for various freeze–thaw cycles.

As it can be observed in Fig. 13, by addition of 3% polypropylene fibers to clay, the sample height increases and then decreases or remains the same. For PF reinforced samples, this height increase or frost heave will decrease up to 70%. For samples reinforced with SF, the height change ratio is about 20%.

During sample preparation and the procedure of mixing water with clay and fiber, it is observed that water has a significant influence on providing cohesion between polypropylene fibers and soil grains. When no water exists in the mixture, polypropylene fibers and soil do not mix properly. A properly uniform mixing is achieved just after adding water. This phenomenon is observed only in sample preparation.

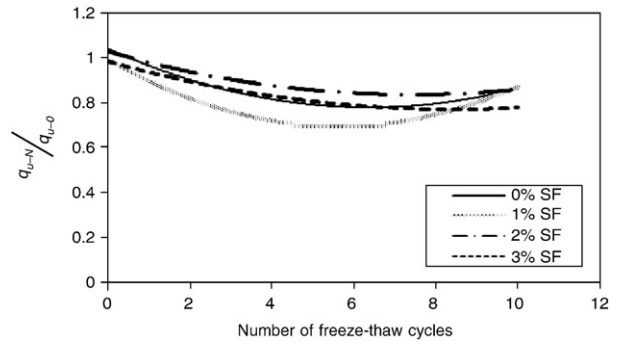


Fig. 11. Ultimate strength ratio for steel fiber-reinforced samples (q_{u-N} = unconfined strength after N cycles; q_{u-0} = unconfined strength with no cycles).

During freezing phase, ice crystals are formed and then, during thawing phase, these crystals start to melt and free water appears in the sample. The free water moves to lower parts of the sample due to gravity force. Consequently, upper parts of the specimen lose their moisture and the adhesion between fibers and soil grains becomes weaker. Therefore, the reinforced sample in thawing phase cannot return to its initial situation before freezing. This phenomenon leads to an increase in the sample height which is more than that of unreinforced sample.

By addition of 3% fiber, the sample height change is affected by the decrease of soil volume and thus, reinforced samples experience less height increase. For a given fiber content in the sample, polypropylene fibers are more effective from this point of view, because they possess smaller unit weight than steel fibers. In other words, polypropylene fibers decrease the sample volume increase more than steel fibers.

The variation of height increase reduction affects the unit weight value as shown in Fig. 14. As it can be seen, in the presence of both

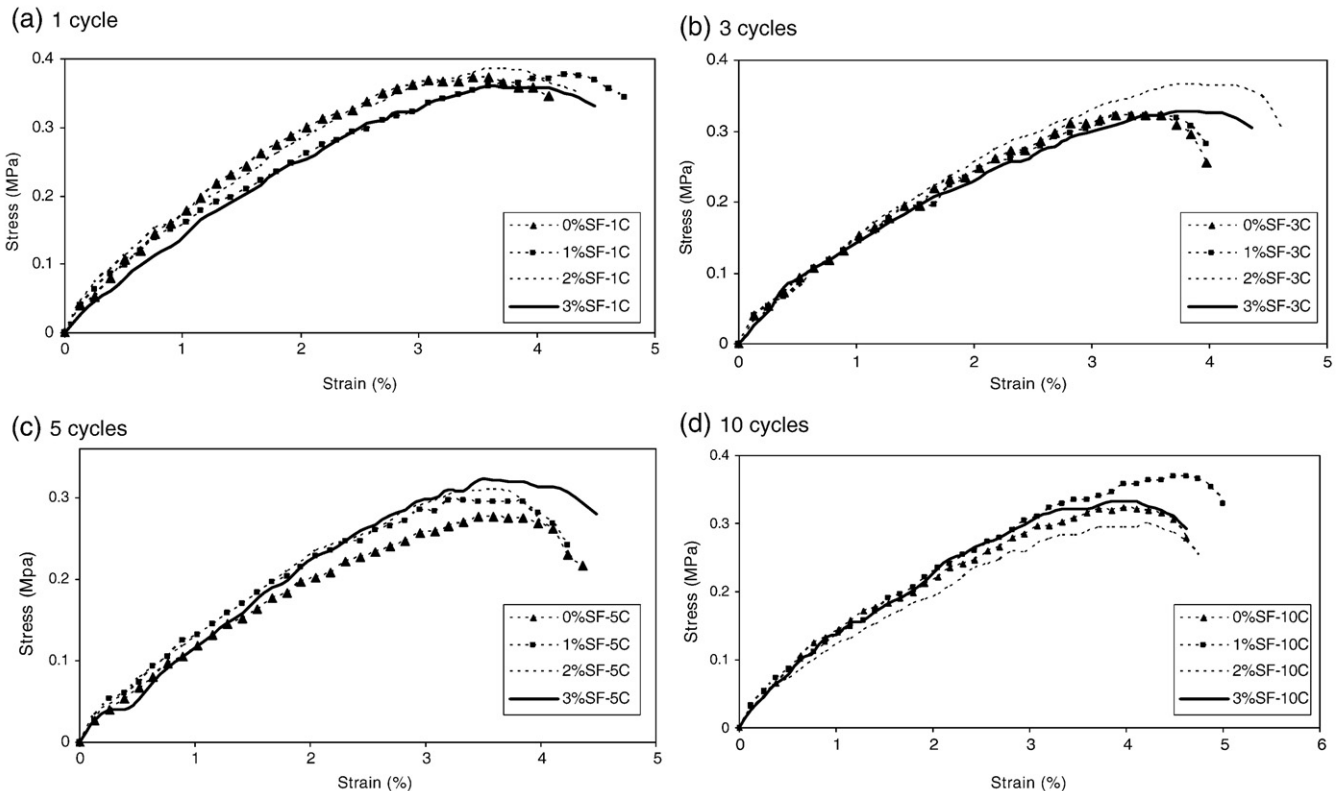


Fig. 10. Stress–strain curves of steel fiber-reinforced samples after 1, 3, 5, and 10 freeze–thaw cycles.

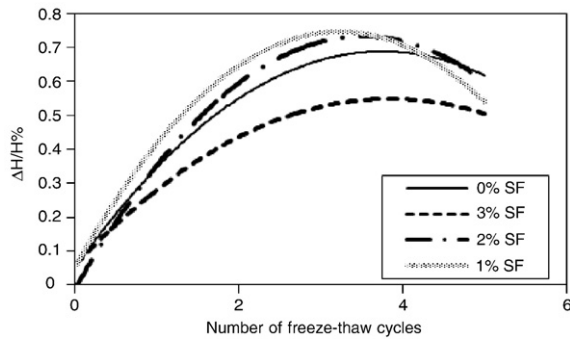


Fig. 12. Height changes of steel fiber-reinforced samples due to freeze-thaw cycles.

fibers, the unit weight of the sample decreases. However, polypropylene fibers are more effective than steel fibers in preventing the unit weight changes. After 10 freeze-thaw cycles, the unit weights of unreinforced samples decrease by about 0.4% more than PF reinforced samples and 0.1% more than SF reinforced samples.

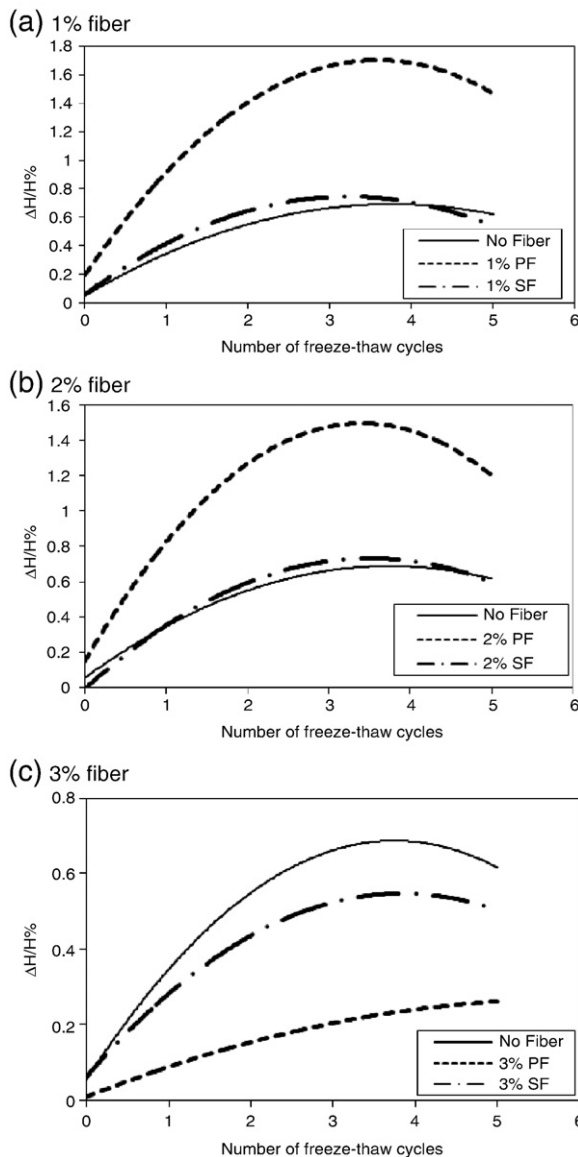


Fig. 13. Variation of height changes for clayey samples reinforced with poly propylene and steel fibers: (a) 1% fiber; (b) 2% fiber; and (c) 3% fiber.

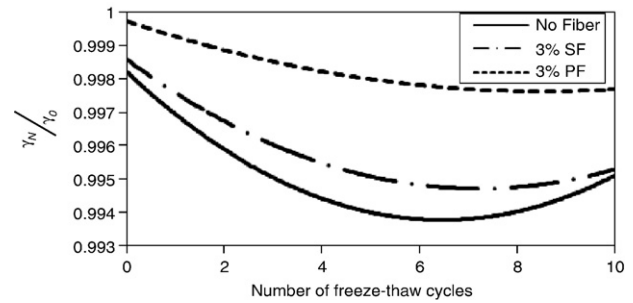


Fig. 14. Unit weight changes of reinforced samples during freeze-thaw cycles.

Based on the results of this research, it can be said that changes in strength and height of samples occur during the first 10 freeze-thaw cycles. Most of the changes occur during the 1st–7th cycles. For the 7th–10th cycles, the changes are not significant since a new equilibrium condition becomes predominant on samples. In this situation, the physical and mechanical characteristics of soil remain relatively constant. In fact, for both unreinforced and reinforced soil, after 7–10 freeze-thaw cycles, the soil properties may be considered constant and are applicable for practical design.

It should be noted that polypropylene fibers do not cause any environmental damage.

5. Conclusions

In this paper, unconfined compression strength tests are conducted to investigate the effects of freeze-thaw cycles on the strength of a kaolinite type clayey soil reinforced by polypropylene and steel fibers. The results show that:

- By increasing the number of freeze-thaw cycles, the unconfined compression strength of all reinforced and unreinforced samples decreases by about 20–25%.
- The addition of 3 wt.% of fibers increases the unconfined compression strength of soil. For polypropylene fibers, the increases are respectively 160% and 60% before and after applying cycles. For steel fibers, these increases are about 7% and 6% before and after applying cycles respectively.
- By increasing the number of freeze-thaw cycles to 5–7, the height of specimens increases. Beyond this range, the height remains almost unchanged.
- The addition of fibers to clayey samples can affect the height changes produced by freeze-thaw cycles. By addition of 1–2% polypropylene fibers, the height increase is augmented compared to the height increase in steel fiber-reinforced samples. By addition of 3% polypropylene fibers, the sample height decreases up to 70%, whereas for the same value of steel fibers, the sample height decreases to about 20%.
- Both of the fibers affect the sample unit weight increase during freeze-thaw cycles. After 10 freeze-thaw cycles, the unit weights of unreinforced samples decrease by about 0.4% more than PF reinforced samples and 0.1% more than SF reinforced samples.
- Based on the changes in strength and height of samples subjected to 1–10 freeze-thaw cycles, it can be said that most of the changes occur at 1st to 7th cycles. For the 7th to 10th cycles, changes are not significant, since a new equilibrium condition become predominant on the samples.
- Generally, based on the findings of this paper, it is recommended that in cold climates, where soil is affected by freeze-thaw cycles, polypropylene fibers are preferable to steel fibers. Polypropylene fibers are also preferred from an environmental point of view.

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