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RESEARCH ARTICLE

A Study on Freeze-Thaw Behavior of Randomly Distributed Fiber-Reinforced Soil

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Abstract

The freeze-thaw behavior and compressive strength of soil play a significant role in various engineering applications, such as dams and clay liners in waste containment facilities. The discrete fiber reinforcement technique was proposed in order to increase the soil's freeze-thaw behavior and its compressive strength. In this study, a series of unconfined compression and freeze-thaw tests were carried out in the laboratory in order to investigate the effects of randomly distributed polypropylene fibers with a length of 3 mm, 6 mm, and 12 mm on a soil. Fiber percentage for each length was determined as 0.15%, 0.20%, and 0.25% of the total dry weight of the reinforced soil. The number of freeze-thaw cycles was taken as 1, 3, 5, and 10. The results of the study indicate that an increase of polypropylene fiber length caused an increase in peak stress values. On the other hand, the peak stress of unreinforced and reinforced soil samples generally decreases when the number of freeze-thaw cycles is increased. Samples reinforced with polypropylene fibers usually behave in a more ductile manner than unreinforced samples.

Keywords

Freeze-thaw · Unconfined compression strength · Polypropylene fiber

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1 Introduction

The concept of reinforcing soil with natural fibers originated in ancient times. Ancient civilizations used straw and hay to reinforce mud blocks in order to create reinforced building blocks [1]. This study has focused on the effects of discrete reinforcement inclusions on the engineering properties of a fine-grained soil. During the last few decades, randomly distributed fiber reinforcements have attracted increasing attention in geotechnical engineering [2–8]. The primary purpose of reinforcing soil mass is to improve its stability, increase its bearing capacity, and reduce settlement and lateral deformation [9–11]. In comparison with conventional geosynthetics, the advantages of using randomly distributed fibers are as follows: a- Randomly distributed fibers are simply mixed with soil, just like mixing soil with additive materials. b- Randomly distributed fibers limit potential planes of weakness that may develop in the direction parallel to the conventionally oriented reinforcement. c- Fibers have no negative effect on the environment [12].

In regions affected by seasonal climatic changes, soil may be exposed to freeze-thaw cycles several times a year. This, in turn, negatively affects some of the engineering properties of fine-grained soils (water content, ultimate bearing capacity, permeability, etc.). Soil properties, in cold regions where temperature falls below 0°C seasonally, must be known before design and construction of structures are built [13]. The freeze-thaw process has more effects on fine-grained soils than on coarse-grained soils [14, 15]. Reinforcement elements are placed in the soil in order to reduce the impact of adverse effects of freeze-thaw phenomenon on some of the engineering properties of fine-grained soils. In comparison with the studies on the compaction and strength characteristics of randomly reinforced cohesive soils [16–30], there are a limited number of studies on the freeze-thaw behaviour of fiber reinforced clays in the literature [14, 29, 34, 35].

In this study, stress-strain and freeze-thaw behaviours of soil reinforced with randomly distributed polypropylene fibers were investigated. A series of unconfined compression and freeze-thaw tests were carried out in the laboratory. Polypropylene fiber lengths and number of freeze-thaw cycles were chosen as parameters in the experiments. The test results for reinforced and unreinforced samples were compared and discussed.

2 Materials and Methods

The soil used in this study was supplied from the Cat, Erzurum, Turkey. The result of the particle size analysis of the soil sample is shown in (Fig. 1). The x-ray diffraction (XRD) method was used to identify the major minerals in the soil (< No.200 sieve) used in the study. The XRD analyses were performed at the General Directorate of Mineral Research and Exploration (Turkey) on air-dried, solvated with ethylene glycol, soil samples which had been heated to 300 and 500°C. The XRD diffractogram of soil samples is shown in (Fig. 2). In this study, polypropylene fiber ('M' type) was used as a reinforcement material. The commercial presentation for the polypropylene fiber and its discrete form used in the experiments are shown in (Fig. 3). The ratio of the fiber (i.e., the content of fiber reinforcement) used in the experiments is expressed in total weight due to the difficulty of determining the volume.

Some of the properties of the soil are given in Table 1. The specifications of some of the properties provided by the manufacturer of the polypropylene fibers are also given in Table 2.

Tab. 1. Some of the properties of the soil used in the experiments

Properties	Value
Specific gravity, G_S	2.55
Liquid limit[1], w_L (%)	42
Plastic limit[2], w_P(%)	21
Plasticity index, I_P(%)	21
Optimum water content[3], w_{opt} (%)	19
Maximum dry unit weight[3], γ_{dmax}(kN/m^3)	17
Unconfined Compression Strength[4], (kPa)	167

[1] w_L per BS 1377 (Part 2-1990)

[2] w_P per ASTM D 4318-00 (2000)

[3] Obtained from Standard Proctor Tests (ASTM D 698-78)

[4] Obtained from the tests on the samples prepared at w_{opt} and γ_{dmax}

Tab. 2. Some of the properties of the polypropylene fiber (supplied by the manufacturer)

Properties	Value
Content	100% pure polypropylene
Appearance	Thin Hair String
Length, (mm)	3 - 6 - 12
Tensile Strength, (N/mm^2)	500 - 700
Elongation, (%)	25
Colour	Transparent
Softening	150 ^{0}C
Melting	160 ^{0}C

The soil used in the experiments was washed through a ASTM200 sieve ($d = 0{,}074$ mm) and dried in an oven at 105 ± 5°C for 24 hours. Polypropylene fiber lengths were chosen as 3, 6, and 12 mm. Fibers were mixed with the dry soil at 0.15, 0.20, and 0.25% of the total dry weight of the reinforced soil for each fiber length. Because the fibers tend to flocculate, a considerable effort was made to achieve a homogeneous distribution of the fibers in the mixtures. The fiber-soil mixture was compacted in three layers into a cylindrical mould (38 mm in diameter, 76 mm in height), with optimum water content and dry density. The specimen preparation method was adapted from the standard compaction test method [31]. These cylindrical samples were used in all of the experiments.

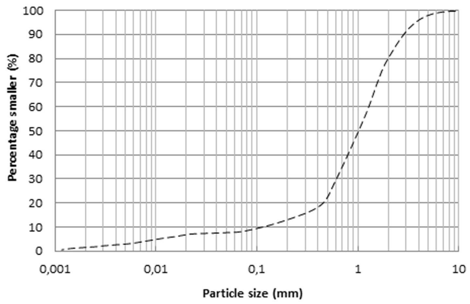
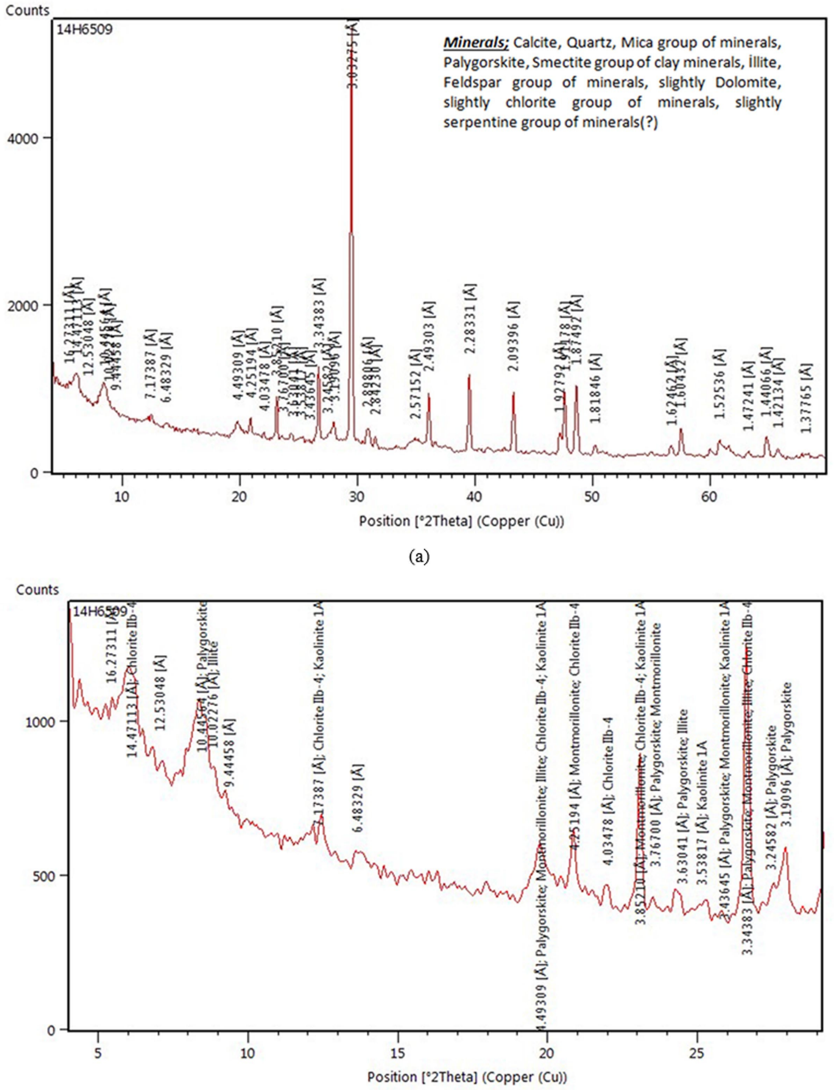


Fig. 1. Particle size distribution curves of soil sample

Freeze-thaw tests were conducted at a minimum temperature of -25°C and at a maximum temperature of 60°C in a programmable freeze-thaw cabinet, with dimensions 110 cm x 55 cm x 55 cm. The programmable freeze-thaw test cabinet is shown in (Fig. 4). These tests were carried out on both reinforced and unreinforced soil samples. Samples, prepared at optimum water content and maximum dry unit volume weight, were wrapped in aluminium foil to avoid changes in their water content [32] (Fig. 4). A thin film layer of Vaseline was spread evenly all over the aluminium foil to prevent the samples from sticking to it [33, 34]. The prepared samples were placed in the programmable freeze-thaw cabinet and tests were performed at -20°C for 6 hours and at 25°C for 6 hours. This operation is referred to in this study as Cycle 1 [35]. The number of freeze-thaw cycles was chosen as 1, 3, 5, and 10. The polypropylene fiber percentages and lengths as well as the number of freeze-thaw cycles were chosen in accordance with the literature [35–37]. The samples were not removed from the programmable freeze-thaw cabinet during the experiments.

Unconfined compression tests were conducted on cylindrical specimens prepared at maximum dry unit weight and optimum moisture content. The unconfined compression tests were carried out in accordance with ASTM D 2166 [38]. The reinforced and unreinforced soil samples were loaded in the deformation-controlled unconfined compression test device at a loading rate of 0.8 mm/min, in order to observe the stress-strain behaviour. In this test, unconfined compressive strength was taken as the maximum load per unit area or the load per unit area at 15% axial strain, whichever occurred first during a test [38]. Each test was repeated on three samples to assure the repeatability of the results. The result of each test was taken as the average of three



Minerals; Calcite, Quartz, Mica group of minerals, Palygorskite, Smectite group of clay minerals, İllite, Feldspar group of minerals, slightly Dolomite, slightly chlorite group of minerals, slightly serpentine group of minerals(?)

(a)

(b)

Fig. 2. A typical XRD analysis result for the soil (< No.200 sieve), (a-For the position of 2Θ between 2°and 70°; b- For the position of 2Θ between 2°and 30°)

samples and stress-strain curves were used for average values. A scaled image of a typical surface of failure in reinforced and unreinforced samples after the unconfined compression tests is shown in (Fig. 5).

Fig. 3. Polypropylene fiber

3 Results and Discussions

The stress-strain curves (σ - ε) obtained from unconfined compression and freeze-thaw tests of samples reinforced by 0.15%, 0.20%, and 0.25% of the polypropylene fibers are shown in Figures 6, 7 and 8, respectively. As can be seen in Fig. 6, the peak stress value of the reinforced soil increases with the increase of fiber length. In the situation where there is no freeze-thaw cycle and 0.15% polypropylene fiber content, the increase in peak stress values of soil samples reinforced with fibers with a length of 3 mm, 6 mm and 12 mm is approximately 9%, 12% and 46%, respectively. It can also be seen that unreinforced soil sample mimics a brittle behaviour for all of the freeze-thaw cycles. On the other hand, the reinforced samples exhibit more ductile behaviour. The initial stiffness of reinforced soil appears to be increased by the addition of fiber.

Fig. 4. Fully automatic freeze-thaw cabinet

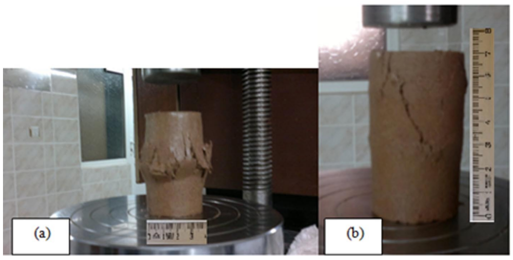


Fig. 5. Typical failure surfaces (a) reinforced – (b) unreinforced

It is believed that this increase might be the result of the mechanical improvement of the load-deformation behaviour, because fibers which are randomly distributed within the soil act as a bridge between soil grains. This phenomenon can be explained by stress transmission from soil to fibers: friction between fiber and soil mobilizes the tensile stresses in fibers when strains in soil mass reach a certain value. Similar results were observed by Singh and Bagra (2013) and Marandi et al. (2008) [7, 8].

As can be seen in (Fig. 6), in general, the peak stress of unreinforced and reinforced soil samples decreases with the increase in the number of freeze-thaw cycles. After freeze-thaw cycles, the highest stress value was observed for the reinforced sample with 12 mm polypropylene fiber.

(Fig. 7) shows the stress-strain curves of unreinforced and reinforced samples for 0.20% fiber ratio. The results also showed generally an increase in initial stiffness modulus with the additive fiber. This increase is more considerable for the 12 mm long fiber reinforced samples. It correlates the interlocking of particles and the bonding between fibers and soil. In other words, the fibers correlate the interlocking of soil particles and these groups of fibers and soil particles behave as a unitary solid matrix, thus may resulted in an increase in soil strength properties [15]. Also, (Fig. 7) clearly shows that the peak stress values of all samples decreased with the increase in the number of freeze-thaw cycles.

The highest unconfined compressive strength in the tests was achieved for the fiber content of 0.25% (Fig. 8). The reinforced samples with 6 and 12 mm long fibers exhibit more ductile behaviour than the others. Also, these samples have the highest strength values under the freeze-thaw cycles. The initial stiffness modulus of reinforced samples, especially for 6mm and 12mm length of fiber is increased more steadily than those of the others.

In summary, the addition of polypropylene fibers has a positive effect on the unconfined compressive strength of the soil. Similar to the findings reported in the literature [2, 4, 11, 29, 35], the test results suggest that the fiber reinforcements can change the brittle behaviour of the clay to a somewhat more ductile (i.e., strain hardening) one. Also, the test results present, in general, a decrease in peak stresses by increasing the number of freeze thaw cycles for both reinforced and unreinforced samples. This decrease may be caused by the capillary holes in the soil formed by polypropylene fibers. Furthermore, the decrease may be at-

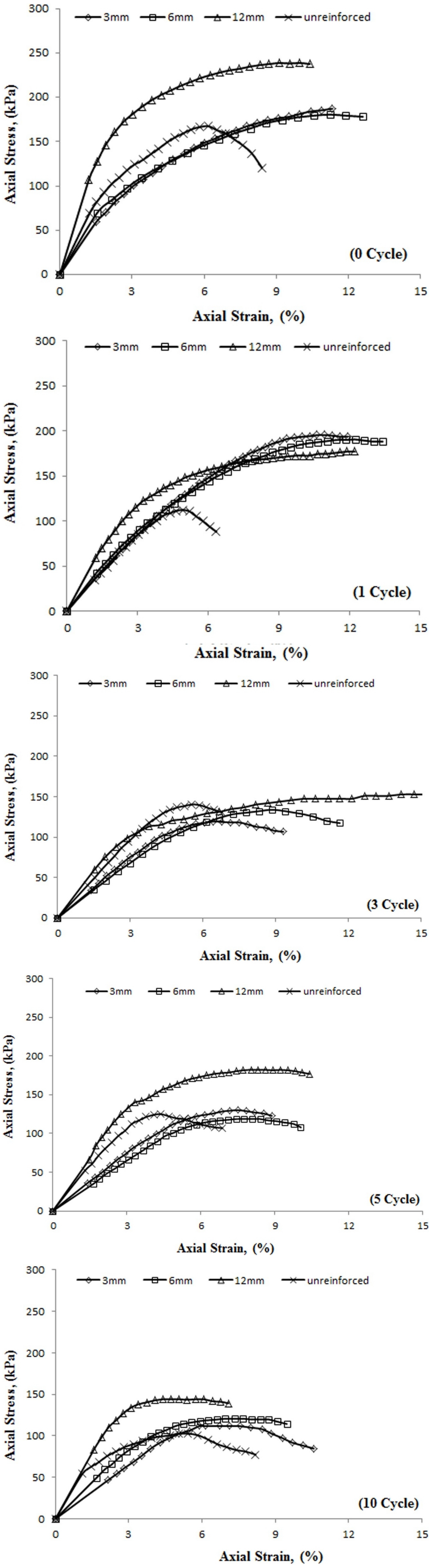


Fig. 6. Stress-strain curves (for 0.15% polypropylene fiber)

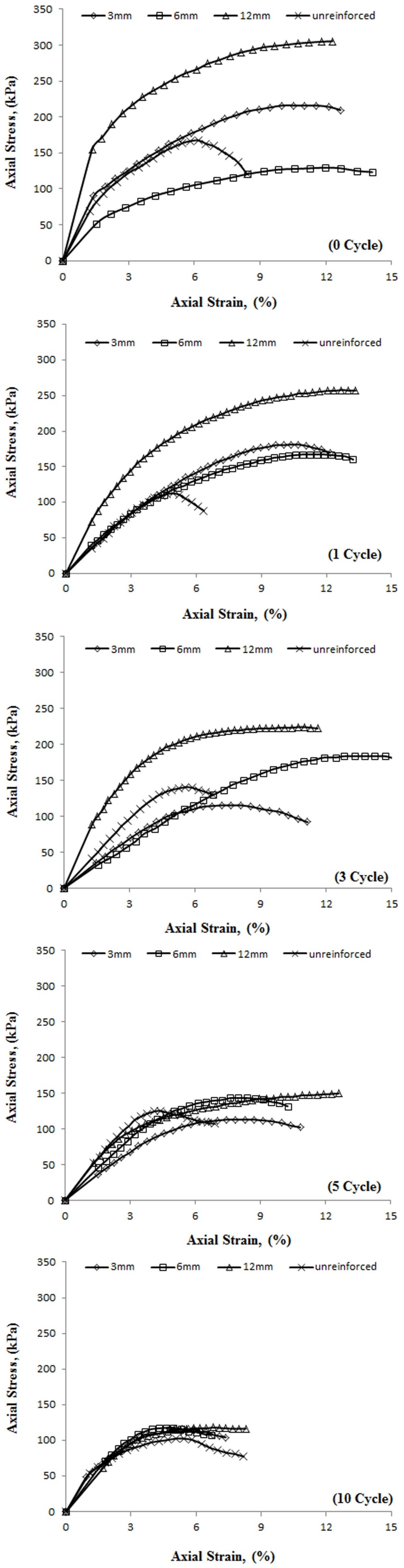


Fig. 7. Stress-strain curves (for 0.20% polypropylene fiber)

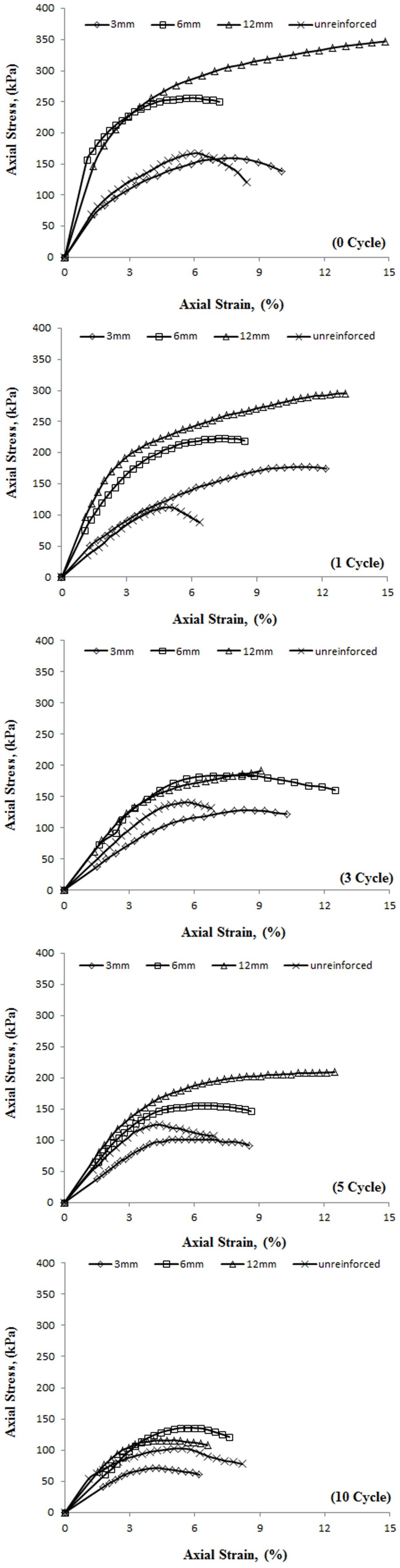


Fig. 8. Stress-strain curves (for 0.25% polypropylene fiber)

tributed to the fact that pore water freezes and forms ice lenses in the pore space between the soil grains, then these ice lenses expand in volume and push grains of the soil and act like springs, increasing gaps among soil grains [39].

It should also be pointed out that fiber orientation has a significant effect on the results. Because of the applied sample preparation method, some changed trends, especially for samples with 12 mm long fibers, could be observed within the experiment series.

4 Conclusions

In this study, a series of unconfined compression tests and freeze-thaw tests were carried out in the laboratory. The main subject of the study was to investigate the freeze-thaw behaviour of soil reinforced with randomly distributed fibers in different lengths and rates. The general results from the tests are as follows:

- The unconfined compression strength of soil could be increased significantly by mixing fibers with soil,
- The unconfined compression strength of reinforced soil increased generally with increasing the polypropylene fiber length and content,
- The reinforced soil samples usually exhibited more ductile behaviour than the unreinforced samples,
- Axial stresses decreased when the number of freeze-thaw cycles increased, for both reinforced and unreinforced samples.

In order to make more realistic judgments on the subject, experiments should be continued for further studies with different polypropylene fiber lengths, soil types, number of freeze-thaw cycles, drainage conditions, time, porosity, void ratio and polypropylene rates. It should also be emphasized that porosity is one of the important index parameters and its development during freeze-thaw cycles is one of the reasons for weakened elastic properties of soil. Further studies to achieve more detailed conclusions should analyse this parameter using the ultrasonic wave propagation test.

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