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Effects of freeze–thaw cycles on a fiber reinforced fine grained soil in relation to geotechnical parameters

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ABSTRACT

Freeze–thaw cycling is a weathering process which occurs in cold climates during winter and spring. At temperatures just below 0 °C, ice lenses which tend to form in free spaces between soil aggregates, force them apart and end up the alteration of characteristic structures in micro and macro scales. In most of the previous studies, changes in physical and chemical properties of soils were investigated. This study was conducted to manifest the effect of using polypropylene fibers in a fine grained soil during freeze–thaw cycles. A clayey soil, reinforced with 0.5, 1 and 1.5 percentages of polypropylene fibers, was compacted in the laboratory and exposed to a maximum of 9 closed-system freeze–thaw cycles. It has been found that for the investigated soil, unconsolidated undrained triaxial compressive strength of unreinforced soil decreases with increasing the number of freeze–thaw cycles, whereas reinforced sample shows better performance and the strength reduction amount decreases from 43% to 32% by reinforcing the soil samples. This effect is caused by acting polypropylene fibers as tensile elements between the soil particles as it is demonstrated with scanning electron microscope (SEM). In addition reinforcing can also reduces the effect of freeze–thaw cycles on the changes of cohesion of the soil.

1. Introduction

In cold climates, soils, especially on shallow depths, are exposed to freeze–thaw cycles every year. These cycles considerably change the engineering properties of soils. During soil freezing, ice lenses which tend to form in free spaces between soil aggregates, force them apart and end up the alteration of characteristic structures in micro and macro scales.

The conditions of ice segregation in frozen soils mainly depend on freezing factors such as temperature, soil types and available free water.

Soil behavior due to freeze–thaw cycles was investigated in numerous studies as in the permafrost regions these cycles reduced the sufficiency of soil structures. In Canada it has been found that the embankment constructed on soil which has never experienced freeze–thaw cycles, was damaged in just one year due to the loss of bearing capacity (Leroueil et al., 1991). Therefore, newly constructed highway embankments that are left unpaved for a few years may be subjected to possible damages by freeze–thaw cycles (Eigenbrod, 1996).

Qi et al. (2006) reviewed the latest efforts which were done to investigate the influence of freeze–thaw cycles on soil properties. They summarized these influences in two parts: physical properties such as density and hydraulic permeability and mechanical properties such as ultimate strength, strain–stress behavior and resilient modulus. As mentioned in this research, loose soils tend to be densified and dense soils become looser after freeze–thaw cycles and both loose and dense soils may attain the same void ratio after a number of cycles (Konrad, 1989). By increasing the large pores that are left after the thaw of ice crystals, permeability will increase (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 that is reduced or may even disappear (Graham and Au, 1985). Resilient modulus is one of the most important factors in pavement designs that will be reduced significantly by even a small number of freeze–thaw cycles (Simonsen and Isacsson, 2001). In addition, these cycles decrease the undrained shear strength considerably which is an important factor in engineering properties of fine-grained soils (Graham and Au, 1985).

It is worth mentioning that the changes of soil microscopic properties during freeze–thaw cycles result in the changes of engineering characteristics of soils. These microstructural changes have been investigated through SEM (scanning electron microscope) and it was found that a very significant increase of the permeability of clayey soil was observed after freezing and thawing (Hohmann-Porebska, 2002) and also the soil becomes looser as the equivalent diameter decreases (Cui et al., 2014).

In addition to static mechanical parameters of soil, the dynamic characteristic changes of soil have been recently considered during freeze–thaw cycles. Wang et al. (2015) found that the dynamic modulus of a silty soil greatly decreases, whereas the damping ratio increases

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with additional freeze–thaw cycles; and changes level off after the sixth cycle. The dynamic properties after 6–7 freeze–thaw cycles are suggested for use in designing and calculating indexes. These results are in agreement with the findings of Cui et al. (2014) who performed dynamic tests on a silty clay.

All above-mentioned research works deal with unreinforced soil. Along with many applications for soil improvement, there come several widely varied methods. Taking the influence of freeze–thaw cycles on soils into consideration, just a few researchers have contemporarily focused on using additives which can control the effects of these cycles.

Yarbesi et al. (2007) stabilized two granular soils by silica fume–lime, fly ash–lime, and red mud–cement. Their experimental results showed that stabilized samples with the mentioned additive mixtures have high freezing–thawing durability as compared to unstabilized samples. These additive mixtures which have also improved the dynamic behavior of the soil samples can be successfully used as an additive material to enhance the freeze–thaw durability of granular soils for road constructions and earthwork applications.

Kalkan (2009) used a fine grained soil stabilized by adding silica fume which was generated during silicon metal production. The test results showed that the stabilized fine-grained soil exhibits high resistance to the freezing and thawing effects as compared to natural fine-grained soil samples. The silica fume decreases the effects of freeze–thaw cycles on unconfined compressive strength and permeability.

Hazirbaba and Gullu (2010) performed CBR tests to investigate the influence of freeze–thaw conditions and also no freeze–thaw conditions on fine-grained soil samples which were treated with the inclusion of geofiber and synthetic fluid in soaked and unsoaked conditions. The results indicated that the addition of geofiber together with synthetic fluid is generally successful in providing resistance against freeze–thaw weakening. However, the addition of synthetic fluid alone is not very effective against the detrimental impact of freeze–thaw cycles. The results from soaked samples subjected to a freeze–thaw cycle show poor CBR performance for treatments involving synthetic fluid, while samples improved with geofibers alone generally offer better performance. Liu et al. (2010) conducted dynamic triaxial tests on cement and lime-modified soils with different blend ratios in freeze–thaw cycles. The results showed that after repeated freeze–thaw cycles, the modified soils exhibit better performance than before modification, the cement-modified clay is superior to the lime modified clay, and all soil mechanical properties are visibly improved.

Zaimoglu (2010) investigated the effect of randomly distributed polypropylene fibers on strength and durability behavior of a fine-grained soil subjected to freezing–thawing cycles. The content of polypropylene fiber varied between 0.25% and 2% by dry weight of soil in the tests. It was observed that the mass loss in reinforced soils is almost 50% lower than that in unreinforced soil. It was also found that the unconfined compressive strength of specimens subjected to freezing–thawing cycles generally increases with increasing fiber content. In addition, the results indicated that the initial stiffness of the stress–strain curves is not affected significantly by the fiber reinforcement in the unconfined compression tests.

Ghazavi and Roustaie (2010) reinforced a caolinite clay with steel and polypropylene fibers and exposed the soil samples to a maximum of 10 closed-system freeze–thaw cycles. They found that increasing the number of freeze–thaw cycles results in the decrease of unconfined compressive strength of clay samples by 20%–25%. Moreover, the inclusion of fiber in clay samples increases the unconfined compressive strength of soil and decreases the frost heave. Furthermore, the results of the study indicated 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%.

The unconfined compression tests have been conducted on clay–polypropylene mixtures after freeze–thaw cycles in previously mentioned researches. As the confining pressure is a factor which causes soil particles to move, rearrange, consolidate, and recover soil strength in a sense, it can be an important factor in determination of soil strength after freeze–thaw cycles (Wang et al, 2007).

In 2014, the stabilization method of soil, affected by freeze–thaw cycles, attracted increasing attention. Unconfined compressive strength (UCS) of gypsum soil samples (gypsum content of 5%, 10% and 25%) decreases greatly, and samples loose substantially all of their strength from the 5th cycle but the lime treated samples without gypsum reveal better durability to freeze–thaw cycles (Aldaood et al, 2014).

The UCS increases with increased bassanite and coal ash contents in the soil. With respect to freezing and thawing durability, the first or second cycle of freeze–thaw, markedly decreases the unconfined compressive strength of both treated and untreated cement stabilized soils, but further cycles have little additional influence (Shibi and Kamei, 2014). Finally Güllü and Khudir (2014) showed that although the potential effective rates of the stabilizers are found to be 0.75% jute fiber, 0.25% steel fiber and 4% lime for soil stabilization but as the freeze–thaw cycles increase, the UCS values decrease at the treatments, except for the additions of jute fiber alone. The jute fiber inclusions relatively decrease the brittleness index toward zero at all freeze–thaw cycles.

Having these results in mind, the present study investigates the effect of confining pressure on the behavior of a fine grained reinforced soil during freeze–thaw cycles. To this end, the strength of the soil reinforced with 0.5%, 1% and 1.5% of polypropylene fibers was evaluated through triaxial test with three different confining pressures (30, 60, and 90 kPa) before and after 0, 1, 3, 6, and 9 freeze–thaw cycles.

2. Materials

In this study, a fine grained soil, classified as CL in the Unified Soil Classification System, underwent laboratory tests. Noticeably, the effects of freeze–thaw cycles are more considerable in fine-grain soils in comparison with sand or gravel (Qi et al., 2006).

The soil properties are presented in Table 1 and its grain size distribution is shown in Fig. 1. Standard Proctor Compaction tests were performed on the soil, and a maximum dry mass density of approximately 1.78 g/cm^3 at optimum moisture content (OMC) of approximately 17.4% was obtained. The specimens are reinforced using 0.5%, 1% and 1.5% of polypropylene fiber contents of weight of dry soil. The properties of the fibers are presented in Table 2.

3. Experimental procedure

This investigation aims at studying the effects of application of polypropylene fibers on the strength changes of highly compressible fine grained soil compacted at maximum dry density with the optimum moisture content and subjected to 0–9 freeze–thaw cycles.

In order to find out the amount of changes of the soil in these cycles, four main following steps should be taken for each sample. Some verification tests are also carried out in order to examine the repeatability of the experiment results.

3.1. Sample preparation

All cylindrical samples with 50 mm diameter and 100 mm height were prepared with the maximum dry unit weight and optimum water content. To prepare samples, firstly, the necessary OMC was determined and mixed with the soil. The soil and the fiber amounts

Table 1
Properties of the soil.

G_s (specific gravity)	2.657
Plastic limit	36%
Liquid limit	20%
Plastic index	16%