Strength development and post freeze-thaw behavior of kaolin reinforced with fibers

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ABSTRACT

In this study, unconfined compression tests have been performed to investigate the effect of freeze–thaw cycles on strength properties of kaolin reinforced with fibers. Kaolin was mixed with bentonite in percentages of 10, 30, and 50 in terms of the dry mass of soil. Bentonite admixed kaolin specimens were prepared at optimum moisture contents and reinforced with varying fiber contents. The specimens were subjected to 0, 1, and 5 freeze–thaw cycles. It was found that fiber inclusion to soil improved the mechanical properties of the soil; the peak strength increased by the existence of fibers and the strength loss after the peak strength decreased. It was also seen that the increment of the plasticity index required more fiber content to achieve a similar amount of compressive strength with the specimens that had a lower plasticity index. The unconfined compressive strength of unreinforced specimens decreased with increasing the number of freeze–thaw cycles, whereas reinforced specimens showed better performance and the strength reduction decreased with the optimum amount of reinforcing content. The lowest values of compressive strength are obtained after the 5th cycles of freezing-thawing of the specimens.

Keywords: kaolin, bentonite, fiber, unconfined compression strength, freeze-thaw cycles

1 INTRODUCTION

The physical and mechanical properties of soils are affected by the freeze-thaw cycles in cold regions. Many geotechnical applications such as embankments, man-made fills, unpaved roads, railroads, buried structures may be vulnerable to climate changes. Damages and loss of bearing capacity may become the major problems due to freezing-thawing.

The freeze-thaw cycles considerably decrease the undrained shear strength which is an important factor in fine-grained soil design (Graham and Au, 1985). Fine-grained soils have a relatively low permeability and during loading they tend to behave as undrained. As a consequence, stability problems in such soils are often controlled by the undrained shear strength. The effect of freeze-thaw on the undrained shear strength has been studied on natural soil specimens as well as laboratory-prepared specimens. It was found that the undrained shear strength decreased significantly for natural clays (Graham and Au, 1985; Leroueil et al. 1991). It was also found that the change was greatest during the first few cycles (Yong et al., 1985).

The use of additives in optimum amounts may improve the performance of fine grained soils under freeze-thaw conditions. In recent times, freeze–thaw performance of fine graded soils with fiber inclusions became a point of interest. Ghazavi and Roustaie (2010) investigated the effect of freeze–thaw cycles on the compressive strength of fiber-reinforced MH soil by exposing the specimens to a maximum of 10 closed-system freezing and thawing cycles. The results of the study showed that the increase in the number of freeze–thaw cycles results in the decrease of unconfined compressive strength (UCS) of clay samples by 20–25%. Inclusion of 3% polypropylene fibers in clay samples increased the unconfined compressive strength of soil before and after applying freeze–thaw cycles by 60% to 160%. Gullu and Hazirbaba (2010) performed UCS tests on ML soil samples treated with fibers and synthetic fluid together. The stress–strain responses of the soil treated with fibers and synthetic fluid in terms of post-peak strength, strain hardening, and ductility were better than that of treated with synthetic fluid alone, emphasizing the importance of fiber inclusions in the soil improvement. Zaimoglu (2010) found that the UCS of MH specimens subjected to freeze–thaw cycles generally increased with increasing fiber content. On the other hand, the results indicated that the initial stiffness of the stress–strain curves was not affected significantly by the fiber reinforcement in the unconfined compression tests and stated that the mass loss in reinforced soils was almost 50% lower than that in the unreinforced soil. Jafari and Esna-ashari (2012) worked on the UCS of lime stabilized clayey soil with fiber (derived from waste material of tire cord factory) reinforcement and...
stated that the compressive strength and stress–strain behavior of specimens depend considerably on the amounts of both fiber and lime and stated that the contribution of fiber in the strength of specimens increased the number of freeze–thaw cycles. Olgun (2013) optimized lime, rice husk ash and fiber amounts for expansive clays under freeze–thaw conditions. Gülüü and Khudir (2014) presented a study on the effect of freeze–thaw cycles on the unconfined compressive strength of low-plasticity silt treated with jute fiber, steel fiber and lime. They proposed a combination of effective stabilizer rates all together, increasing the unconfined compressive strength performances together with cost–benefit advantages.

This study examines the strength characteristics of fiber reinforced fine grained soil under the condition of freeze–thaw cycles. Kaolin was mixed with bentonite in percentages of 10%, 30% and 50%, in terms of the dry mass of soil using optimum water contents of each mixture. Bentonite is formed by mostly montmorillonite type of clay minerals, which exhibits extreme engineering properties; therefore bentonite was admixed to kaolin to obtain qualitative discussion. The specimens were reinforced with fibers using 0.1%, 0.5%, and 0.75% fiber contents of weight of dry soil. Some specimens were subjected to one or five cycles of closed-system freezing and thawing. Then unconfined compression strength tests were conducted on the specimens. The main aim of this study was to investigate the effect of fiber content on the strength of different types of fine grained soils subjected to freeze-thaw cycles.

2 MATERIALS

The soils of kaolin and bentonite from Canakkale mines in Turkey were selected for this study. The kaolin and bentonite soils were classified as ML and MH, respectively, according to the Unified Soil Classification System (USCS). For kaolin and bentonite soils, chemical analyses were provided by the production company which denoted kaolinite and Na montmorillonite minerals constitute the dominant fraction of the soils, respectively. The engineering properties of the soils are shown in Table 1.

| Properties                     | Values |
|--------------------------------|--------|
| Liquid limit (%)               | 46     |
| Plastic limit (%)              | 33     |
| Plasticity index (%)           | 13     |
| Optimum moisture content (%)   | 32     |
| Maximum dry unit weight (kN/m²)| 13.4   |
| USCS classification            | ML     |
|                                | MH     |

The mixtures of kaolin with 10%, 30%, and 50% of bentonite were all classified as MH. In the text, these mixtures are abbreviated as 10B, 30B, and 50B, respectively. Pure kaolin specimens are named as 100K.

The fiber materials used in this study were also produced in Turkey by a local company. Table 2 presents some technical properties of the fibers.

| Properties                      | Specifications | Values |
|--------------------------------|----------------|--------|
| Composition                    | 100% virgin polypropylene | Fiber length | 12mm |
| Type                           | Fibrillated     | Tenacity | 6.5-7.0g (high) |
| Cross section                  | Rectangular    | Tensile strength | 300-400 (MPa) |
| Standard                       | ASTM C 1116    | Young’s modulus | 1000-2500 (MPa) |
| Color                          | Transparent    | Specific density | 0.91 (g/cm³) |

3 TESTING PROCEDURES

The scope of the paper is to study the effect of adding polypropylene fibers on the strength characteristics of kaolin soils mixed with varying percentages of bentonite which are exposed up to 5 cycles of freeze–thaw. For each fiber content percentage, at least 3 specimens were prepared and subjected to 0, 1, and 5 freeze–thaw cycles. Some verification tests were also carried out in order to examine the repeatability of the experimental results.

3.1 Specimen preparation

The moisture content of each kaolin–bentonite mixture was predetermined by compaction testing and these moisture contents were also used in fiber added conditions. The optimum moisture contents versus dry unit weights are presented in Fig.1. The mixtures of soil were divided into three parts. Each part was placed in the mold and was compacted. The preparation of polypropylene reinforced specimens was a rather difficult task. To overcome this difficulty, the required amount of water was added to the soil prior to adding the fibers. Fibers were mixed manually with the wet soil at small increments. Particular care was taken to achieve satisfactory uniform mixtures.

Fig. 1. Compaction curves of bentonite admixed kaolin (K: kaolin, B: bentonite).

After compactions of the natural soils and the
soil–fiber mixtures, cylindrical samplers were pressed into the compacted samples within the mold to obtain samples with appropriate length to diameter ratios for unconfined compressive tests. Then the cylindrical unreinforced and reinforced samples taken into the cylindrical samplers were extruded from the cylindrical samplers using a hydraulic jack. The specimens were cylinder-shaped with 50 mm diameter and 100 mm height.

3.2 Unconfined compression tests
The UCS values of unreinforced and reinforced samples were determined from the unconfined compressive tests in accordance with ASTM D2166. This test is widely used as a quick and economical method of obtaining the approximate compressive strength of the cohesive soils. The loading rate was 1.42 mm/min until samples failed in the test.

3.3 Freezing-Thawing tests
Closed system freezing in a soil is a condition in which no source of water is available during the freezing process beyond that originally in the voids of the soil at or near the zone of freezing; ice lenses may or may not form (Jones, 1987). In many cases the closed system provides a reasonably close approximation of the field conditions (Wong and Haug, 1991). In freeze–thaw tests, one group of soil specimens was subjected to one freeze–thaw cycle as the detrimental effects of freeze–thaw cycles reported to occur during the first cycle (Lee et al., 1995; Qi et al., 2008). Another group of specimens was subjected to five freeze–thaw cycles to see the effects of further deterioration. The freeze–thaw tests were performed by a programmable freezing–thawing apparatus. The process of freeze–thaw tests were held in accordance with ASTM C666. The specimens were placed in a freeze–thaw apparatus and conditioned between −18 °C and +15 °C for 2.30 h. After the test was completed, the specimens were transferred from the freezing apparatus into a test room at +20 °C.

4 RESULTS AND DISCUSSION
The following paragraphs will explain a selection of stress–strain behavior derived from the results of the unconfined compression tests. Because of the large number of tests in this study, only selected test results indicating the variety of stress–strain curves with bentonite content, fiber content, and freeze-thaw effects are presented.

4.1 Effect of bentonite content
The variation of unconfined compressive strength (UCS) with bentonite content at various compaction water contents is shown in Fig. 2. Three specimens were prepared for each case and UCS values showed a linear decrement by the addition of bentonite clay. Each group in the same bentonite content showed small changes in measured UCS values confirming the accuracy of test results. The reduction in shear strength is partly attributed to the increase in bentonite particles that filled voids between kaolinite particles, which lowered the frictional resistance between the soil particles at their contact points.

![Fig. 2. Variation of unconfined compressive strength with bentonite content for three groups of specimens.](image)

4.2 Effects of fiber content
Fiber inclusion to soil improved the mechanical properties of the soil; the peak strength increased by the existence of fibers and the strength loss after the peak strength decreased. The highest value of UCS was achieved as 353 kPa in pure kaolin specimens that contained 0.75% of fibers with 80 kPa increment compared to fiber free specimens of the same kind. The increase in the UCS was attributed to the bridging effect of fibers which efficiently impeded the further development of failure planes and deformations of the soil.

![Fig. 3. Stress-strain curves of kaolin specimens with varying fiber ratio (FR=fiber ratio).](image)

The initial stiffness of soil appears not to be affected by the addition of fiber reinforcement for pure kaolin specimens (Fig. 3). It can also be seen that the fiber reinforced soils exhibit more ductile behavior than the unreinforced soil (Figs. 3&4). The increment of the plasticity required more fiber content to achieve a similar amount of compressive strength with the
specimens that had lower plasticity.

Fig. 4. Exemplary stress-strain curves of bentonite admixed specimens reinforced with fibers (FR=fiber ratio).

4.3 Effect of freeze-thaw cycles

The effects of freeze–thaw cycles on the compressive strengths of specimens were determined by the freeze–thaw tests. The test results of specimens having 0% and 0.75% fiber ratios which were subjected to 1 and 5 cycles of freeze-thaw are considered in Fig. 5 to evaluate the minimum and maximum fiber ratios of this study. There was a decrease in the compressive strength with increasing freeze–thaw cycles. It was observed that the effects of freeze–thaw cycles on the compressive strength varied depending on main soil and additive soil, and fiber content.

Fig. 5. Remaining strength percentiles of kaolin–bentonite mixtures (without fibers or with a fiber ratio of 0.75%) after freeze-thaw cycles.

The term ‘remaining strength’ was used and defined as the ratio of the UCS of the specimen that experienced no freeze-thaw cycles to the UCS of the specimen that experienced freeze-thaw cycles. Remaining strength was between 40% and 90% for specimens that experienced 1 cycle of freeze thaw. The strength properties of soil specimens without fiber content were more affected by increasing freezing–thawing cycles. The remaining strength was between 35% and 80% for specimens that experienced 5 cycles of freeze-thaw.

The major deterioration was observed in specimens that contained pure kaolin without fiber inclusions. Although the UCS of bentonite admixed kaolin specimens were lower than the kaolin specimens, the loss of strength in percent was less in bentonite admixed specimens. This might be due to the resistance of bentonite to cracking and keeping a stable hydraulic conductivity during freeze-thaw cycles. However, the addition of fibers improved the freezing–thawing durability of stabilized samples as compared with unreinforced samples. The improvement rate was between 1.49 and 2.70 times of the unreinforced specimens. Even introduction of 0.1% fiber improved the post-freeze thaw performance of the specimens.

5 CONCLUSIONS

Cost-effective solutions are highly preferred in geotechnical engineering applications by the addition of fibers, which may improve the stress–strain and strength properties of the fine grained soils. In this study, the effects of polypropylene fibers on the unconfined compressive strength of bentonite admixed kaolin mixtures under freeze-thaw cycling have been investigated.

In bentonite admixed clay specimens that were free of fibers, it was seen that increment of bentonite percentage in the mixture decreased the UCS of the specimens.

The unconfined compression test results indicated that the shear strength increased with the addition of fibers and bentonite admixed kaolin soil behavior was changed to a more ductile behavior. The strengths of the specimens increased with polypropylene fiber content. The highest value of UCS was achieved as 353 kPa in pure kaolin clay specimens with 0.75% fiber content. However, the stiffness of 50% bentonite admixed kaolin soil decreased, which might be due to the introduction of a medium that was more plastic than the kaolin soil.

After the application of freeze-thaw cycles the UCS results show that the specimens lose some part of their shear strength, but with the addition of small quantities of polypropylene fibers, this loss of strength could be partially prevented. The remaining strength percentage was higher in the specimens with bentonite rather than the pure kaolin specimens due to its highly plastic nature.

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