Effect of Freeze–Thaw Cycles on the Strength of a Nanosilica and Lime Treated Clay

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Abstract In this study, the unconfined compressive strength of a clay treated with nanosilica and lime was investigated under freeze–thaw conditions. The specimens were prepared at their corresponding optimum water contents and compacted under a standard Proctor compactive effort. The pure clay and the clay treated with 5% lime were subjected to freeze–thaw cycles to determine the strength changes of specimens. The maximum number of cycles applied to the specimens was 10. The cycles were applied in 12 h intervals and the temperature range was ±18 °C. Subsequently, the clay was treated with 0.3, 0.5, 0.7 and 1% nanosilica and 5% lime. The clay specimens showed a tendency to decrease in strength as a result of freeze–thaw cycles. The maximum strength loss observed was around 41%. It was concluded that, it was not possible to achieve sufficient amount of improvement by using solely nanosilica in the clay specimens. The unconfined compressive strength of nanosilica and lime treated clay accelerated with curing time. Besides, the strength loss of specimens due to freeze–thaw cycles could be partially prevented with the addition of nanosilica and lime. Consequently, usage of nanosilica together with lime, resulted in a better improvement, even if the soil was subjected to freeze–thaw cycles.

Keywords Clay · Unconfined compressive strength · Freeze–Thaw cycles · Nanosilica · Quicklime

1 Introduction

The environmental conditions have an impact on the variation of the soil properties. Freezing of the ground is a seasonal phenomenon that can be encountered frequently in many parts of the world [1]. The freeze–thaw effects, especially on soils with expansive clay content, frequently cause great damage and costs to structures. It is an important issue to improve the properties of soils for freezing and thawing [2].

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Bell [3] determined that the mineralogy of clay was a very important in the stabilization of the soils. The soil mineralogy and temperature criteria were efficient on the plasticity and strength gain rate of the soil, and the success of the stabilization. Bell [4], inspected the lime stabilization of clays with different mineralogies. When lime is added to the clay soils, calcium ions interact with clay minerals up to the lime fixation point. Lime is effective in terms of workability rather than strength up to the optimum lime content. Kaolin reacts to the lime later than montmorillonite, but montmorillonite would not have a higher late strength than kaolin [4]. Dash and Hussain [5] investigated the lime stabilization using quicklime in high and low plasticity soils. They pointed out that the presence of excess lime in silica-rich soils in which silica gel was formed, gave a rise to the reduction of the overall strength. The silica gel led to increased plasticity and swelling of the soils.

Zhang [6] presented that even a small amount of nanoparticles could be important on the behavior and mechanical properties of soils due to the high surface area of the nanoparticles affecting the physico-chemical behavior of the soils. Changizi and Haddad [7] assessed the effect of nanosilica particles to improve the mechanical properties of low and high liquid limit clay soils. The nanosilica Dash and Hussain ratios used in the study were determined as 0.5, 0.7, and 1.0%. The unconfined compressive strength increased by up to 56%. With the increase of nanosilica content, the deformations measured at the time of failure decreased and the elastic modulus values increased. The addition of nanosilica significantly improved the mechanical properties of the clay. Moayed et al. [8] investigated the interaction of kaolin clay and nanosilica in their study. The soils specimens treated with nanosilica contents ranging from 1 to 5% were examined. The remarkable increase in uncondfined compressive strength was observed at 4% nanosilica content. Although nanosilica has been the point of focus, different nano-sized materials such as nano-copper, nano-clay and nano-magnesium nano-ZnO were also investigated in the literature [9, 10].

Kalhor et al. [11] subjected nanosilica treated fine-grained soils to nine freeze–thaw cycles, and recommended 2% nanosilica addition to the soils. Shahsavani et al. [12] reported that extension of curing time improved the unconfined compressive strength of the slag and nanosilica treated specimens against the freeze–thaw cycles.

Different types of additives have a possible use in the soil improvement, but the types of additives that can provide environmentally friendly solutions are limited. Nanosilica additive is in the "green binder" category and as a new additive, its full effect on soils have not been revealed yet [13]. Besides, the freeze–thaw behavior of the nanosilica added soils has been merely studied.

This study deals with the freeze–thaw cycle effects on characteristics of a clay soil stabilized with nanosilica and lime. Atterberg limits, compaction, unconfined compression and freeze–thaw tests are performed to observe the changes in the soil properties.

2 Materials and Testing Methods

2.1 Materials

The kaolin clay was derived in powder form from a local quarry and it was classified as a high plasticity silty soil MH according to ASTM D2487 [14]. ASTM D4318 [15] was followed in the determination of Atterberg limits, and ASTM D698 [16] was followed for the standard compaction test. The liquid limit of the soil was 52%, the plastic limit was 34%, and the plasticity index was 18%. The optimum water content of the soil was 32%.

Quicklime was preferred as a stabilizing agent. The lime was obtained from a quarry company. The chemical analysis of lime showed that 95.6% was CaO and 0.9% was MgO and the remaining was trace elements. The nanosilica particles were purchased from Molchem Industries Ltd.; they were 15 nm in size with a purity of 99.5%.

The lime content of the study was 5% by the dry weight of the soil. The nanosilica contents used in the study were 0.3, 0.5, 0.7 and 1%.

2.2 Testing Methods

The specimens of unconfined compressive tests and freeze–thaw tests were prepared in the following manner: First, the dry soil and lime were mixed. Then, nanosilica was mixed in the water for 5 min with a high speed (120 rpm) mixer and added to the dry mixture. The water contents of the specimens were adjusted to their optimum water contents. The specimens had a diameter 50 mm and a length of 100 mm. The specimens were covered with an airtight film to secure the water content and placed in a moisture room until the end of their curing time. The temperature of the moisture room was 23 ± 2 °C with a relative humidity of 90–95%.

The freeze–thaw tests were carried out on the specimens when the curing period was completed. In the freeze–thaw tests, the specimens were exposed to 5 or 10 freeze–thaw cycles. The freeze thaw tests were performed according to ASTM D560 [17]. The freezing temperature was in the range of -18 ± 2 ºC and the thawing temperature was in the range of $+18 \pm 2$ °C. The time for each freezing or thawing action was 12 h; 1 cycle was completed in 24 h. The specimens were subjected to the unconfined compressive tests after their completion of the freeze–thaw cycles by following ASTM 2166 [18].

3 Results and Discussion

3.1 The Effect of Lime

The Atterberg limits of the 5% lime treated soil were determined. The liquid limit and the plastic limit of the treated soil was 75 and 44%, respectively. The rise in the Atterberg limits was due to the action of hydroxyl ions which modified the affinity of the surfaces of the clay particles for water. The plasticity properties obtained within the short-time of the test were governed by the rearrangement of clay particles induced by the addition of lime and not by bonding induced by the pozzolanic reactions [19].

The compaction tests of clay and lime treated clay were carried out separately (Fig. 1). With the addition of 5% lime to the soil, the maximum dry unit weight decreased and the optimum water content of the treated soil increased. The optimum water contents and the maximum dry densities of clay and lime treated clay soils were 32 and 38%, and 1.60 g/cm^3 and 1.50 g/cm^3, respectively.

The specimens were subjected to the unconfined compressive tests after the freeze–thaw cycles were completed. The clay soil had a strength of 205 kPa. After 5 and 10 cycles of freeze–thaw, the strength of the clay decreased to 192 and 160 kPa, respectively. The 5% lime treated specimen which was cured for a day and then subjected to 10 cycles of freeze–thaw resulted in a strength of 195 kPa. The strength of 5% lime treated clay was 312 kPa after 7 days and it increased to 408 kPa after 28 days.

In Fig. 2, it is seen that the behavior of clay has changed from ductile to brittle behavior with the action of freeze–thaw. The natural clay reached its peak strength at a strain of 6.09%, while the axial strain of clay after 10 cycles of freeze–thaw was 1.89%. Lime addition also contributed to the brittle behavior of the clay. The stress–strain curve of 28-day specimen of 5% lime treated clay is also given in Fig. 2.

Fig. 1 The optimum water content of clay and lime treated clay

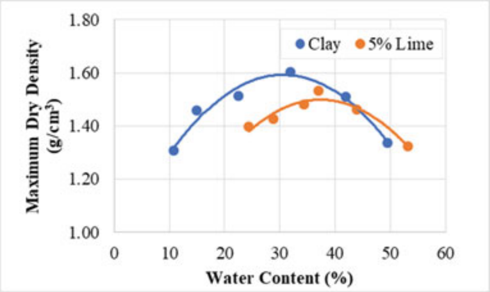
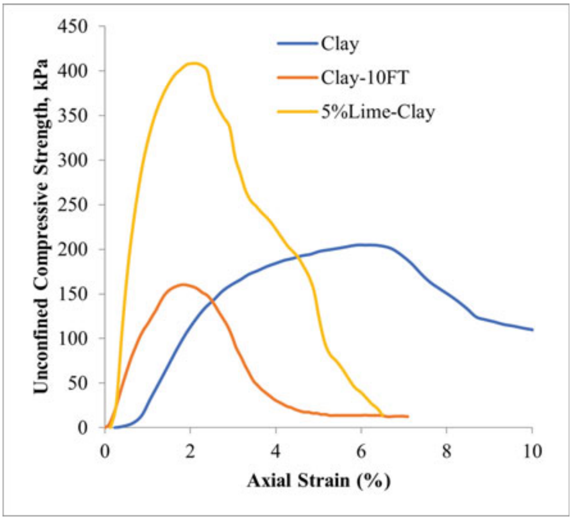


Fig. 2 Stress–strain curves of the specimens



3.2 *The Effect of Nanosilica*

In order to examine the effect of the nanosilica on the strength, the specimens containing 0.3, 0.5, 0.7 and 1% nanosilica were prepared. The contribution of nanosilica was evident even in 1-day specimens (Fig. 3). The gradual increase of the strength was observed among 0.3, 0.5, and 0.7% nanosilica treated specimens. However, there was a decrement of strength in 1% nanosilica treated specimens. The excessive rate of nanosilica had a strength reducing effect rather than contributing to it. The addition of 0.7% nanosilica increased the strength to 305 kPa after 28 days and this strength was almost 1.5 times of the strength of the untreated clay soil. Therefore, the optimum nanosilica content was 0.7% in clay specimens. Changizi and Haddad [20] and Hu et al. [21] expressed that when water was added to the clay, the nanosilica particles produced a viscous gel across the diffuse double layer of the clay particles. Due to the viscous gel, the bonding force between the clay particles was much stronger than the absorbed water. The viscous gel reduced the distance between particles and increased the particle contact. The cohesion between the clay particles due to the viscous gel was stronger than the cohesion between the clay particles, due to the presence of absorbed water [7]. The viscous gel filled the macropores in the clays to some extent [21, 22].

When the 28-day specimens of 0.7% nanosilica treated and 5% lime treated specimens were compared, it was seen that lime treatment was still superior in terms of strength. For this reason, a better stabilization could be achieved with the simultaneous application of nanosilica and lime to the soils.

The effects of 5 and 10 freeze and thaw cycles were investigated on the nanosilica treated specimens. The cycles were consecutively repeated in this study until its effect on the soil strength became negligible, which was termed as an equilibrium [2,

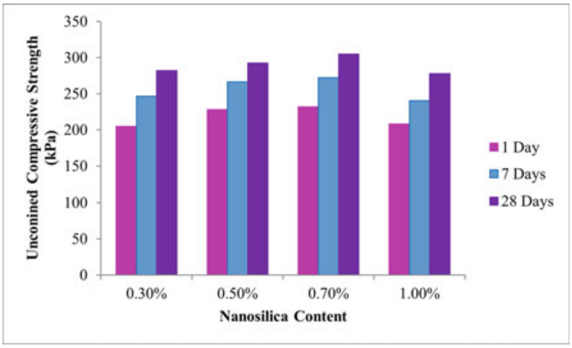


Fig. 3 The strength of clay treated with different nanosilica contents

11]. The strength loss of 5 cycles of freeze–thaw was more pronounced compared to the strength loss of the specimens that were subjected to 10 cycles (Fig. 4). The soil strength reduction occurred in earlier cycles and after 5 to 10 cycles the strength reduction would reach to an equilibrium condition [23]. The strength decreased remarkably in 0.3 and 1% nanosilica treated specimens after 5 cycles of freeze–thaw. The strength of the specimen in 0 cycle was accepted as 100%, and the strength reduction calculated in percentage from this value was called "strength loss". The strength loss of 0.7% nanosilica treated specimens was 16%, while the strength loss of 1% nanosilica treated specimens was 41%, indicating the deterioration level of the specimens after 10 cycles of freeze–thaw. Although trace amounts of nanosilica were used in this study, 0.5 and 0.7% nanosilica treated specimens kept the majority of their strength against the freeze–thaw cycles. In order to reinforce the binding effect of the soil particles, using nanosilica together with an additive such as lime would also help to prevent the deteriorations against freeze–thaw.

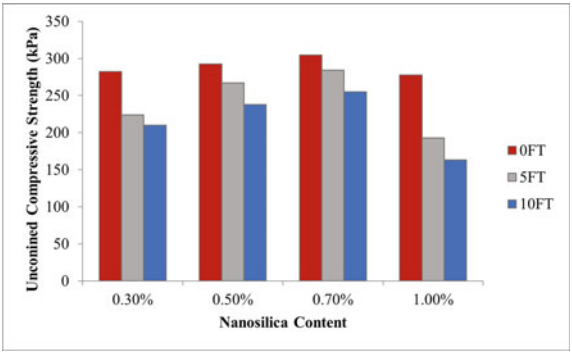


Fig. 4 The effect of freeze–thaw cycles on the nanosilica treated clay

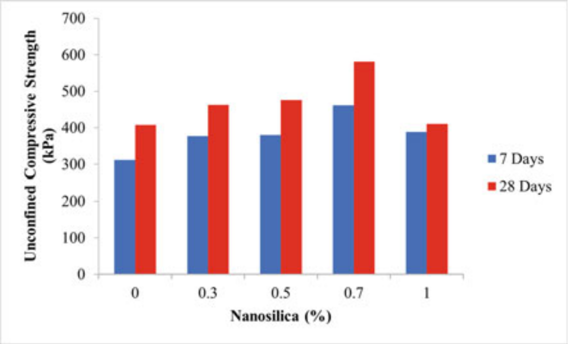


Fig. 5 The strength of the clay treated with nanosilica and lime

3.3 *The Binary Effect of Nanosilica and Lime*

According to the results of the unconfined compressive strength tests, the highest strength was achieved with 0.7% nanosilica-5% lime treated clay after 28 days (Fig. 5). The 28-day strength of the specimens treated with 0.7% nanosilica and 5% lime was 125% higher than their 7 day strengths. The 28-day strength of the same specimen was 581 kPa and it was the highest strength among the experimental groups.

An evaluation of the strength decrement of 7-days 0.7% nanosilica-5% lime treated specimens showed that, at the end of 5 freeze–thaw cycles, the strength of the specimens was 409 kPa. After 10 freeze–thaw cycles, the strength of the specimens decreased to 373 kPa. This result showed that the strength of the treated specimens had 1.82 folds more strength compared to that of untreated clay. Adding lime to the soil caused long-term pozzolanic reactions and nanosilica had an accelerating effect on the reactions in the soil medium. Besides, the formation of viscous gel increased the durability of the specimens when they were subjected to freeze–thaw cycles.

4 Conclusion

The effect of nanosilica and lime treatment on the unconfined compressive strength of a clay soil was assessed. The outcomes of the study are as follows:

(1) As a result of lime treatment of the clay soil, the maximum dry unit weight decreased and the optimum moisture content of the soil increased.
(2) The unconfined compressive strength decreased with freeze–thaw cycles in the clay and the lime treated clay. The strength of the clay was 205 kPa and the strength of 5% lime treated clay was 221 kPa. After 10 cycles of freeze–thaw, the strength of the clay and 5% lime treated clay decreased to 160 and 195 kPa, respectively.

(3) The addition of nanosilica at different rates from 0.3 to 1% on clay soil showed some strength gain between 7 and 28 days. The highest strength was obtained with 0.7% nanosilica content. However, the strength of solely lime treated specimens were greater than the specimens that were treated with solely nanosilica.
(4) The unconfined compressive strength of the specimens treated with the optimal amount of nanosilica and lime was 2.25 and 2.83 folds of the untreated clay after 7 and 28 days of curing, respectively. These results were the highest strength values obtained among the other experimental groups. The strength of 7-day specimens obtained after 10 freeze–thaw cycles was 373 kPa, being 1.82 times more than the strength of the untreated clay.

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