Jurnal
Teknologi

Full Paper

THE INFLUENCE OF FREEZE–THAW CYCLES ON UNCONFINED COMPRESSIVE STRENGTH OF CLAY SOILS TREATED WITH LIME

Article history
Received
22 February 2015
Received in revised form
23 March 2015
Accepted
1 August 2015

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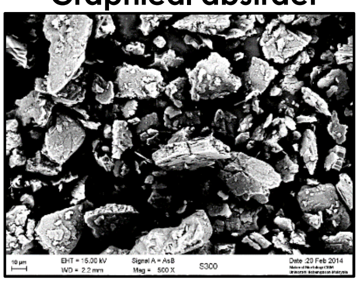
Graphical abstract



Abstract

There are several questions that are not well understood with respect to the long-term stability characteristics of lime-treated clay soils in spite of being used as a conventional technique to improve the properties of clay soils. This paper investigates the influence of freeze-thaw cycles on the unconfined compressive strength of kaolinite and illite mixed with silica sand. The results of this study show that an increase in the number of freeze-thaw cycles decreases the unconfined compressive strength. The role of lime increasing the soil strength is more significant in the case of samples exposed to freeze-thaw cycles compared to those not exposed to freeze-thaw cycles. The effect of freeze-thaw cycles on the dry unit weight and moisture content is insignificant compared to unexposed samples. The maximum volumetric changes occurred in the first freeze-thaw cycle, and afterward, the rate of volume change decreased with an increase in freeze—thaw cycles.

Keywords: Kaolinite, illite, freeze-thaw cycles, UCS, hydrated lime

Abstrak

Terdapat beberapa soalan yang tidak dapat difahami berkenaan dengan ciri-ciri kestabilan jangka panjang tanah liat yang dirawat dengan kapur walaupun digunakan sebagai teknik konvensional untuk meningkatkan sifat-sifat kandungan tanah liat. Kertas ini mengkaji pengaruh kitaran beku-cair pada kekuatan mampatan tak terkurung kaolinit dan ilit yang bercampur dengan pasir silika. Keputusan kajian ini menunjukkan bahawa peningkatan dalam bilangan kitaran beku-cair mengurangkan kekuatan mampatan tak terkurung. Peranan kapur dalam meningkatkan kekuatan tanah adalah lebih ketara dalam kajian kes iaitu sampel yang terdedah kepada kitaran beku-cair berbanding dengan yang tidak terdedah kepada kitaran beku-cair. Kesan kitaran beku-cair pada unit berat kering dan kelembapan kandungan adalah tidak penting berbanding dengan sampel yang tidak terdedah pada kitaran beku-cair. Perubahan maksimum isipadu matrik berlaku dalam kitaran beku-cair yang pertama, dan selepas itu, perubahan isipadu menurun dengan peningkatan dalam kitaran beku-cair.

Kata kunci: Kaolinit, illite, kitaran beku-cair, UCS, kapur terhidrat

1.0 INTRODUCTION

Lime stabilization is one of the initial methods utilized to improve strength over the long term. It has substantially become in the practice of civil engineering like footings, roadbeds, embankments and piles. When the lime is mixed with soils, it leads to improve a lot of engineering characteristics of soils. Many investigators discovered that the strength behavior of soils significantly increases after lime treatment [1]-[4]. The study of Bell shows that soils treated with lime experienced distinctive increases in optimum water content, while considering a decrease in maximum dry density. It is noted that the solid cementation bonds between soil particles, added by lime-soil responses, may resist the forces applied efficiently, which often led to the decrease of compressibility of marine soils [5]. On the basis of the investigations with expansive soils, it is indicated that both swell rate and swell pressure decrease to zero using the lime admixed to soils [6]. In cold regions, the soils are exposed to at least one freezing and thawing cycle every year. The freezing and thawing of the soils can cause significant changes of the geotechnical properties [7], [8]. Clay soils influenced by freezing and thawing show changes in volume, strength and compressibility, densification, unfrozen water content, bearing capacity, and microstructure. In the freezing period, subsoil moisture moves towards the frozen layer because of a temperature gradient. Ice in various sizes and shapes tends to segregate in soils resulting in the formation of characteristic structures in micro and macro scales [9]. In the thawing period, thawing of the frozen layer begins from the top and the bottom at the same time [10], [11]. Several works have been performed to investigate the effects of freezing and thawing on the geotechnical properties of fine-grained soils [12]-[16]. Some authors have showed that the strength of soils decreases. They have seen a reason of such behavior in low freezing rate, preconsolidation pressure developed during freezing formation of new bonding between soil fabric units, and changes in free water [17]-[20]. The main objective of this study was to investigate the effect of freeze-thaw cycles on confined parameters of clayey soils. The parameters investigated in this study include moisture content and unconfined compressive strength.

2.0 EXPERIMENTAL PROCEDURE

The clay minerals used in this study were kaolinite and illite. Silt which was mixed with clay minerals in the present study was silica sand with fine grained particles (45 μm). Kaolinite and illite clay minerals were obtained from Kaolin (Malaysia) factory under the trade name of "S-300" and "KM800" respectively. Table 1 & 2 present the properties of kaolinite and illite, which were determined during this study by performing a series of geotechnical laboratory experiments using procedures recommended by relevant ASTM standards. The lime used in this experimental was hydrate lime [$Ca(OH)_2$]. The chemical content of hydrated lime used in this study is given in Table 3. In Figure 1, 2 and 3, scanning electronic microscopes (SEM) images and in Figure 4 and 5 X-ray Diffraction (XRD) is given which show the kaolinite, illite and silica sand layers.

Table 1 Physical property of materials

Kaolinite		Illite	
Moisture content	Below 1.5%	Moisture content	Below 2.0%
pH	4.0	pH	4.5
100 mesh residue	Below 10%	325 mesh residue	Below 3.0%
60 mesh residue	Below 0.5%	Average particle size	2.5-5.0μm
Specific gravity (Gs) ASTM D854	2.723	Specific gravity (Gs) ASTM D854	2.701

Table 2 Chemical compositions of clay minerals and silica sand

Kaolinite		Illite		Silica Sand	
Formula	Concentration (%)	Formula	Concentration (%)	Formula	Concentration (%)
SiO_2	85.76	SiO_2	29.43	SiO_2	97.29
Al_2O_3	9.11	Al_2O_3	52.37	Al_2O_3	2.71
Fe_2O_3	0.38	Fe_2O_3	1.85	-	-
K_2O	1.34	K_2O	8.21	-	-
Heat loss	3.41	MgO	1.76	-	-
-	-	TiO_2	1.36	-	-
-	-	Heat loss	5.02	-	-

Table 3 Chemical contents of hydrated lime

Chemical contents		**Quantity**
Calcium Hydroxide	$Cao\ (OH)_2$	90%
Magnesium Oxide	MgO	3%
Calcium Carbonate	$CaCO_3$	6%
Arsenic	As	11 p.p.m
Lead	Pb	8 p.p.m

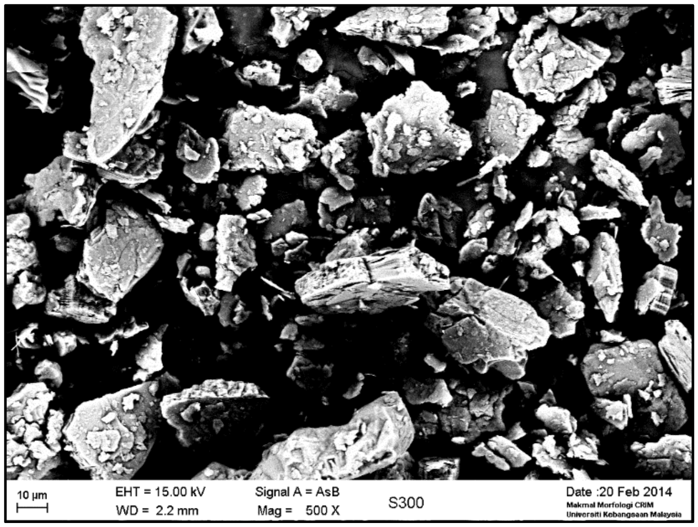


Figure 1 Kaolinite particles under SEM

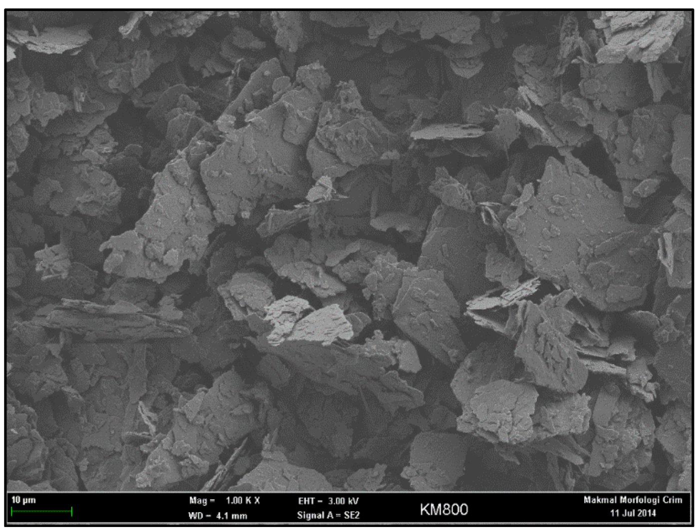


Figure 2 Illite particles under SEM

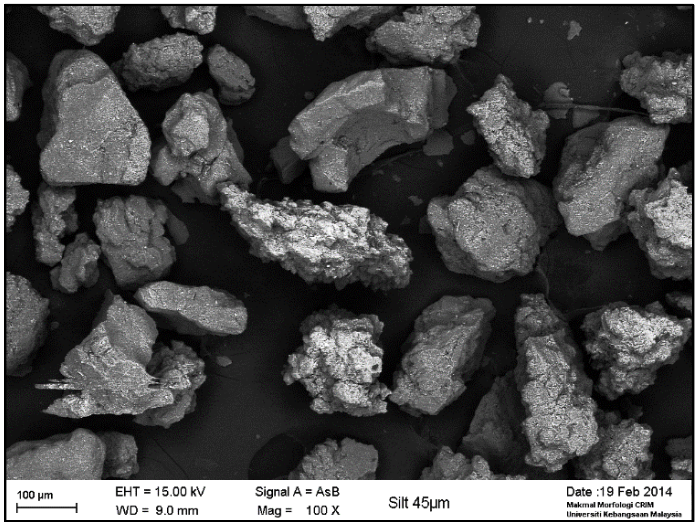


Figure 3 Silica Sand particles under SEM

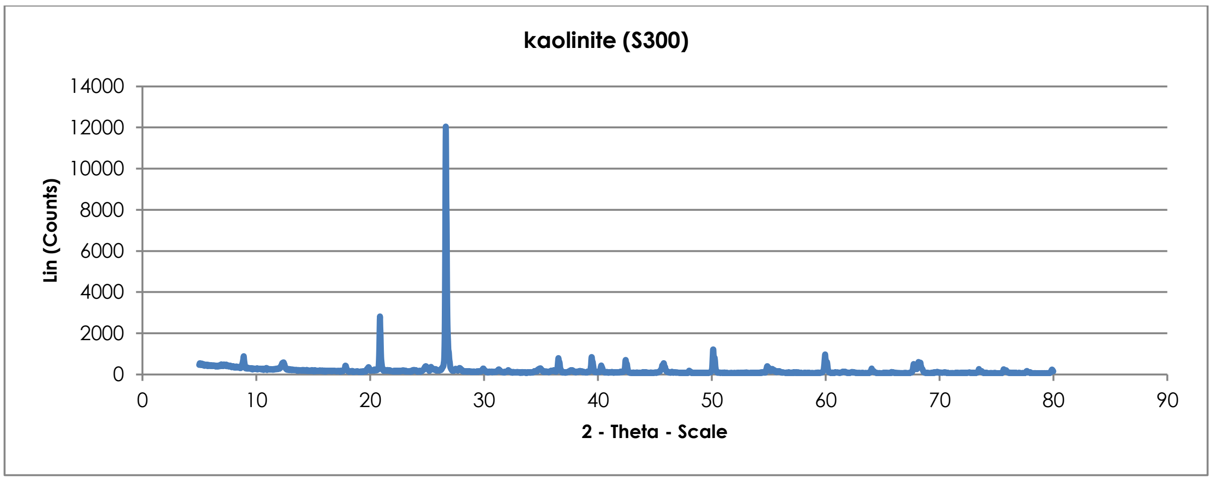


Figure 4 XRD patterns for kaolinite (S300)

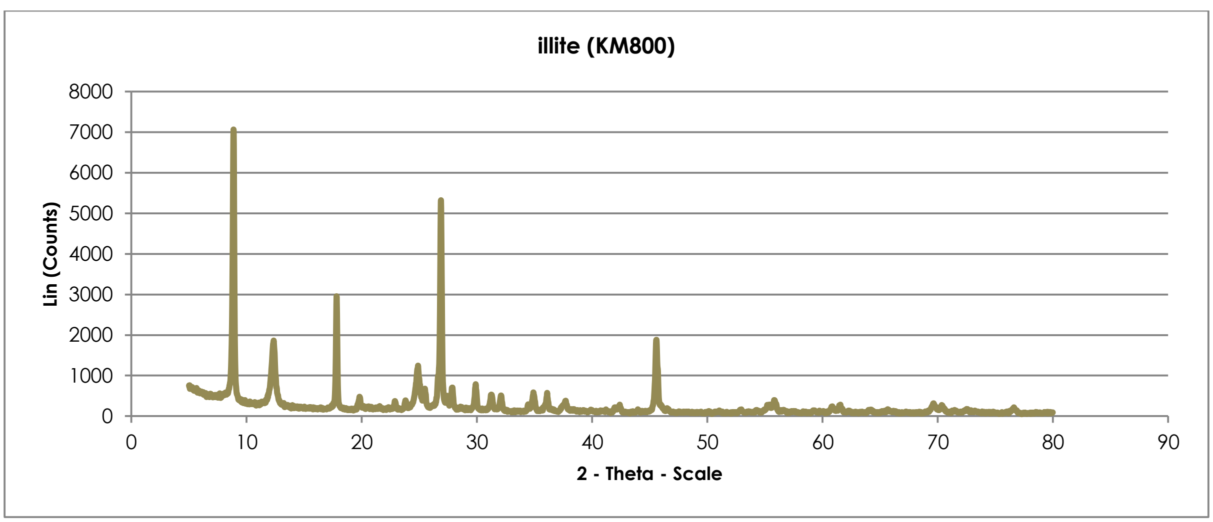


Figure 5 XRD patterns for illite (KM800)

The mix selected for the test was 80% clay (kaolinite/illite) + 20% silica sand with different dosages of lime (1%, 3%, 5% and 7%). Physical properties including plastic and liquid limits, maximum dry unit weight and optimum water content of untreated and treated specimens were determined by using ASTM standards D7382 and D2216 respectively [21], [22]. For the unconfined compressive strength experiment, soil samples were compacted with standard Proctor test (D1557: 3 layers, 25 blows per layer) and then tested in accordance with ASTM D2166-06. Soil specimens were compressed until the failure under a strain rate of 1.5 mm/min. and deformations were noted during the whole test [23], [24].

3.0 OPTIMIZATION PERCENTAGE OF LIME

Two independent methods proposed by Eades and Hill were used to determine the optimum lime percentage for the clay soil [25], [26]. In the first method, suggested by Eades [25], a minimum pH value of 12.4 is necessary to activate the pozzolanic reaction between the lime and the soil. The alkalinity of the soil increases with the addition of lime. The pozzolanic reaction increases as the pH value increases and contributes to achieve better flocculation. The expansive clay undergoes major transformations in its structure when mixed with lime. Flocculation and coagulation contribute to bring several expansive soil particles together to form larger sized aggregates. The change in the soil structure is a consequence of cation exchange caused by dissociated bivalent calcium ions in the pore water replacing univalent cations that are normally attached to the negatively charged individual expansive soil particles.

The pH values measured in the soil specimens for various lime percentages are shown in Table 4. pH of a soil-water mixture containing various amounts of lime by mass is measured. According to this method, a minimum of 3% lime is necessary to achieve a pH value of 12.4.

In the second method, suggested by Hill [26], which is referred to as the minimum lime percentage or "lime fixation point" method, Lm is given by the following equation (1):

$$L_m = \frac{\text{clay content } (<2\mu m)}{35} + 1.25 = 4.88 \qquad (1)$$

Taking into consideration the above-mentioned methods, it was decided to use 5% lime to treat the soil (for both mixture kaolinite and illite). Nevertheless, percentages of 1, 3, 5, and 7%, were tried which supported the choice of 5% lime giving favorable results for stabilization of clay soils.

Table 4 The pH values for various lime percentages

Lime (%)	pH Value	
	80%Kaolinite+ 20%Silica Sand	**80%Illite+ 20% Silica Sand**
0	4.55	3.92
1	6.87	6.00
3	9.33	9.12
5	12.67	12.10
7	12.90	12.78

4.0 FREEZE–THAW CYCLES

Closed-system freezing was applied for the testing of freeze–thaw cycles. The closed system can be described as a freezing process, where no source of water is available during the process beyond that originally in the voids of the soil [27]. This type of freezing system is suitable for the soil conditions when no significant change in the in situ water content is expected between winter and summer seasons. In addition, for the low permeable soil used in this study, the rate of frost penetration is generally obtained more than the rate of moisture transportation so that there is no sufficient time available during freezing to allow a continuous supply of water to reach the freezing front. Hence, a closed system freezing was adopted in this study. For the freeze–thaw tests, the specimens were subjected to 1, 2 and 3 freeze–thaw cycles. The freezing and thawing of samples have been conformed to the procedure given in ASTM 560 [28]. For the freezing, the specimens in the freezing apparatus were subjected to the temperature of -15 °C for 24 h to obtain a complete frost penetration. Then, they were allowed to thaw at a temperature of 22 °C for 24 h in a container within the room having the relative humidity of 100%. The reason of usage for the freezing temperature of -15 °C and the thawing temperature of 22 °C is that they typically represent the temperatures for the silica sand used in this study in order to provide a complete frost penetration (i.e., at -15 °C) and a complete thaw weakening (i.e., at +22 °C). After the freezing and thawing process of corresponding cycles (i.e., 1, 2, and 3), the specimens were performed for UCS testing.

5.0 RESULT AND DISCUSSION

The determination of the effective rates of stabilizers has been concerned with the non-freeze thaw conditions (i.e., zero F–T cycle). The highest UCS values of the stabilizers are separately found as 7% lime for both kaolinite and illite mixture. The rate of 5% lime has been taken as the effective rate in the combinations of stabilizers because the highest UCS gain (i.e., 381 kPa for illite mixture and 359 kPa for kaolinite mixture) that is obtained by 7% lime addition is very close to the UCS gain by 5% lime addition. The 5% rate of lime will also provide an economical point of view to the mixture design. It is shown from Figure 6 that while the UCS of native soil increases from 92 kPa to 131 kPa for kaolinite mixture at the dosage rate of 1%, it approximately increases to 359 kPa for the remaining rates of 3%, 5%, and 7%. Therefore, the potential rate of lime has been selected as 5% to be effective mentioned above. It is well known that the lime is stiffer and stronger than the natural soil, thus it increases internal cohesion in the soil treatment. But, it could exhibit tensile cracking as a major mode of failure. It can be said that the UCS value of native soil (without treatment) decreases with the increased F–T cycles. Thus, this finding relatively proposes the treatment of the native soil as it has been done in this study. As shown from Figures 7 and 8, all treatments present better UCS values than the ones of native soil under F–T cycles.

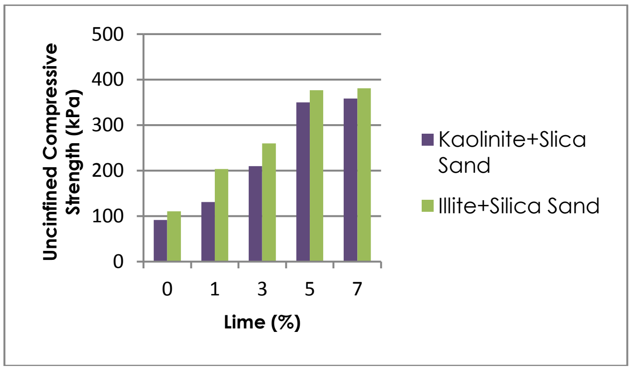


Figure 6 The effects of lime content of the unconfined compressive strengths

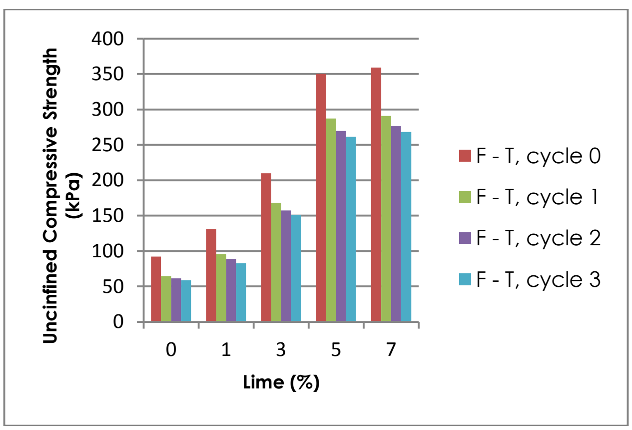


Figure 7 UCS values for all freeze – thaw cycles, Kaolinite mixture

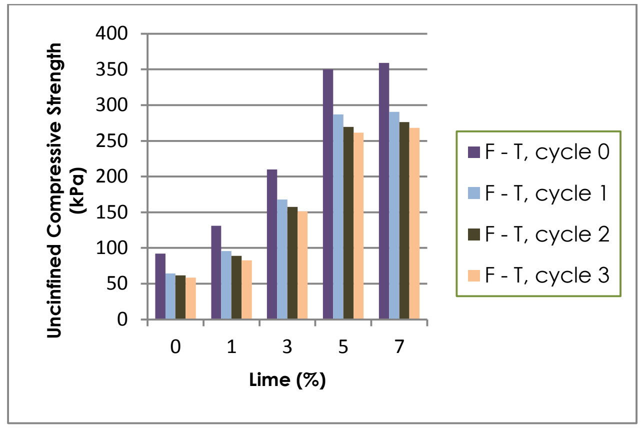


Figure 8 UCS values for all freeze – thaw cycles, Kaolinite mixture

6.0 CONCLUSION

The long-term efficiency of the treatment of kaolinite and illite mixed with silica sand using lime was studied in this study on the basis of freeze - thaw cycles tests. All the tests were carried out on specimens compacted at optimum moisture content and maximum dry density conditions to simulate the possible exposure of a typical clay soils to climatic changes in road construction, or other civil engineering applications. The main conclusions of this research are:

i. From the stress–strain curves, the stress–strain behaviors of the energy-absorption capacity and strain-hardening behavior of native soil are best performed with the inclusion of the lime at all F–T cycles.
ii. The treatment of the specimens with 5% lime results in an overall improvement of most of the mechanical properties of the kaolinite and illite by increasing the shear strength and reduction in volume change and swelling pressure properties.
iii. Lime treatment induces changes in the pore size distribution. Typically, the pore volume increases with a refinement of the pore structure. These structural changes contribute to increase in the coefficient of permeability of the specimens.
iv. Lime inclusions significantly increase the brittleness index.

Acknowledgement

We acknowledge and appreciate the financial support and facilities provided by Geotechnical Engineering lab of Universiti Kebangsaan Malaysia (UKM) for this study and Fuel Cell Institute for SEM tests.

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