Scientia Iranica A (2012) 19 (4), 1013–1017

Sharif University of Technology

Scientia Iranica

Transactions A: Civil Engineering

www.sciencedirect.com

Effect of freezing and thawing on strength and permeability of lime-stabilized clays

M. Yıldız, A.S. Soğancı *

Department of Civil Engineering, Faculty of Engineering & Architecture, Selcuk University, 42075-Campus, Konya, Turkey

Received 30 January 2012; accepted 7 May 2012

KEYWORDS

Freeze-Thaw;
Lime stabilization;
Clay soils;
Unconfined compression test;
Permeability.

Abstract In this study, the effect of freezing and thawing on the strength and permeability of two clayey soils (high and low plasticity), which had been stabilized with lime, were investigated. Before and after stabilization, the permeability and strength of the specimens were determined with various freeze-thaw cycles. Results of this study indicated that for both clays, 6% lime addition increased the hydraulic conductivity of the specimens 1000 times. However, the hydraulic conductivity of clay with 6% lime increased 10–20 times after only 3 freeze-thaw cycles. The results of strength tests exhibited different trends. The strength of stabilized high plasticity clay increased approximately 15 times at the end of 28 day curing, whereas the strength of stabilized low plasticity clay increased about 3 times only. The strength of both stabilized clays decreased 10–15% at the end of the freeze-thaw cycles.

1. Introduction

Soil stabilization has been widely used to increase the strength of subgrade soils for a long time. When fine grained soils are compacted at optimum moisture content, their bearing capacity can be enough. When the water content increases, there is a risk of loosing the bearing capacity. In this situation, lime stabilization is one of the oldest methods used to increase strength over the long term [1]. There are two major objectives of the lime stabilization process, with respect to the improvement of clayey subgrade soils, to improve workability and increase strength [1]. The first objective is attained by decreasing the Plasticity Index (PI) and volume change characteristics of the subgrade soil. The second objective is to increase the strength of the subgrade soil over the long term. Physical and chemical events occur in lime stabilization. These physical and chemical events occur in cement stabilization too [2].

Improvement of clay soils with calcium based stabilizers, such as Portland cement and lime, involves four distinct processes.

- Cation exchange.
- Flocculation and agglomeration.
- Cementitious hydration.
- Pozzolanic reaction.

Portland cement provides the compounds and chemistry necessary to achieve all four processes. Lime can accomplish all the processes except cementitious hydration.

Hydrated lime is calcium hydroxide, designated in chemical form as $Ca(OH_2)$. Hydrated lime is produced by reacting quicklime with sufficient water to form a white powder. Hydrated lime is the form of lime used in the majority of lime stabilization procedures. This process is referred to as slaking. In words and in chemical form, this reaction is denoted as:

High Calcium Quicklime + Water ⇢ Hydrated Lime + Heat

$CaO + H_2O \dashrightarrow Ca\,(OH2) + \text{Heat}.$

Almost all fine grained soils display some cation exchange when treated with lime. The reaction is quite rapid on soils that are finely pulverized and intimately mixed with lime. The cations can be listed in approximate order of their replacement ability. In order of increasing replacement power, the ions are as follows.

$Li^+ < Na^+ < H^+ < K^+ < NH_4^+ << Mg^{++} < Ca^{++} << Al^{+++}$ [3]. Monovalent cations are more easily

* Corresponding author. Tel.: +90 332 223 1986; fax: +90 332 241 0635.
E-mail address: alisoganci@selcuk.edu.tr (A.S. Soğancı).

Peer review under responsibility of Sharif University of Technology.

Production and hosting by Elsevier

1026-3098 © 2012 Sharif University of Technology. Production and hosting by Elsevier B.V. Open access under CC BY-NC-ND license.
doi:10.1016/j.scient.2012.06.003

replaced by multivalent cations. The addition of lime to soil in adequate quantities provides an excess of Ca^{++} to trigger a cation exchange. Typically, lime [$Ca(OH)_2$] stabilizes a sodium clay soil by replacing the sodium ions (Na^+) in the clay's exchange complex, since calcium has a greater replacement power than sodium [3]. The other important reaction is the pozzolanic reaction in soil-lime stabilization. With the addition of lime, aluminous and silicious minerals in clay react with the lime to produce calcium silicates and aluminates that bond the particles together. Cement, however, provides its own pozzolans and, therefore, only requires a supply of water. Pozzolanic reactions are time and temperature dependant, with lime hydration requiring more hydration time than cement [4]. Carbonation is produced by a reaction of lime with atmospheric carbon dioxide to form relatively insoluble carbonate, which is not useful in the stabilization process. This detrimental chemical reaction should be avoided by properly expedited and sequenced construction procedures that prevent prolonged exposure of lime to air [5]. The physical events in soil-lime mixture are flocculation, reduction in plasticity, reduction in volume change, change in maximum density and optimum moisture content, and change in strength and deformation characteristics. When fine grained soil freezes, ice lenses form in the pores, and when the temperature of soil drops below 0 °C, water expands by about 9%. This event causes cracks in the soil.

Chamberlain and Gow [6] examined thin sections of frozen sedimented silt and clay and found horizontal ice lenses perpendicular to the direction of freezing, and vertical ice-filled shrinkage cracks that were linked to form columns with polygonal cross sections. Othman and Benson [7] investigated the effect of compaction conditions (molding water content and compactive effort) and external conditions (temperature gradient, ultimate temperature, dimensionality of freezing, number of freeze-thaw cycles and state of stress) on the hydraulic conductivity of three compacted clays of different properties. Laboratory studies indicate that the number of freeze-thaw cycles, rates of freezing and states of stress have the largest effect on the change in hydraulic conductivity. The hydraulic conductivity increases as the rate of freezing and number of freeze-thaw cycles are increased and as the overburden pressure is decreased. Other factors, such as the ultimate temperature, dimensionality of freezing, and availability of an external supply of water, do not appear to have a significant effect on the change in hydraulic conductivity. The effect of freezing and thawing on the strength characteristics of clay soils has not been researched by these researchers. Pousette et al. [8] reported that freeze/thaw cycles detrimentally affect strength gain for several types of peat with moisture contents in the range of 200%. In their investigation, stabilized peat samples exposed to eight freeze/thaw cycles (-10 °C/ $+$ 20 °) lost 30% of their strength as compared to those that were not exposed to these cycles. Thompson and Dempsey [9] showed that if adequate lime is available, pozzolanic reactions will continue to occur under favorable conditions.

2. Materials

In this study, two types of soil that have different plasticity were used. While Soil-1 from Doğanhisar (Konya) had low plasticity (CL), Soil-2 from Ortaköy (Aksaray) had high plasticity (CH). Classification, Some geotechnical and chemical properties of these materials are given in Table 1. Hydrated high-calcium lime [$Ca(OH)_2$] was used as a stabilizer. In this study, strength and permeability alterations of two types of clay sample during curing were studied. These samples were also subjected to the freezing-thawing process during curing.

Table 1: Classification, geotechnical and chemical properties of materials used.

Properties		Aksaray clay	Doğanhisar clay
Maximum dry unit weight (kN/m^3)		1421	1632
Optimum moisture content (%)		26.46	17.50
Specific gravity		274	270
Liquid limit (%)		72	46
Plastic limit (%)		27	24
Plasticity index (%)		45	22
SiO_2 (%)		60.86	54.19
CaO (%)		2.66	0.58
Classification	AASHTO	A -7 -6	A -7 -6
	USCS	CH	CL

3. Testing procedures

3.1. Preparation of samples

The type of preparation of pure clay samples is different from samples stabilized with lime. For pure clay samples, distilled water was lightly sprayed onto the material. For lime stabilized clay samples, firstly, 6% lime was mixed with dry clay samples, then, water was added. The ASTM D698-78A [10] method was used in the compaction tests. As Daniel and Benson [11] recommended, both clay and lime were compacted at water content at about 2% of optimum water content using standard Proctor compaction, because soil liners have traditionally been compacted in the field over a specified range of water content. Lime stabilized samples were cured for 1, 3, 7, 21 and 28 days at room temperature. Before curing, samples were wrapped with nylon film, and then covered with aluminum foil and put into nylon bags so as not to lose their water content. When the curing times ended, a series of unconfined compression tests and permeability tests were conducted on the samples.

3.2. Permeability test

Falling-head tests were used to determine the hydraulic conductivity of specimens, according to ASTM D 5084-03 [12]. Specimens were prepared in 102 mm diameter Proctor molds. These specimens were subjected to 3 freeze-thaw cycles, according to ASTM D 560-03 [13], after which permeability tests were conducted. Three freeze-thaw cycles were determined as the minimum number of cycles.

3.3. Unconfined compression test

Unconfined compression tests were performed on compacted soil-lime samples in accordance with ASTM D 2166-06 [14]. Soils were treated with 6% lime and compacted at optimum moisture content. After the compaction test, soil specimens were taken with thin steel tubes ($D = 37$ mm in diameter, $H = 74$ mm in long) for an unconfined compression test. Each sample was placed in a plastic bag and cured for 1, 3, 7, 21 and 28 days in a moist room at 22 °C, and some specimens were subjected to freeze-thaw cycles with curing. The specimens prepared were put in the loading machine and centered in it. The loading plate was loaded until it touched the specimen. At that point, the dial gauge was calibrated. The loading procedure was performed until 15% deformation occurred.

4. Results

For various curing times, the permeability results of Aksaray and Doğanhisar clays are presented in Tables 2 and 3.

Table 2: Results of permeability tests for Aksaray clay.

Specimen	Curing time (day)	k (cm/s) (without freeze-thaw)	k (cm/s) (with freeze-thaw)	% Change of permeability
Without lime	0	7×10^{-7}	7×10^{-7}	0
%6 lime	1	1×10^{-6}	1×10^{-5}	900
%6 lime	3	5×10^{-6}	7×10^{-5}	1300
%6 lime	7	1×10^{-5}	8×10^{-5}	700
%6 lime	21	5×10^{-5}	1×10^{-4}	100
%6 lime	28	9×10^{-5}	2×10^{-4}	1222

Table 3: Results of permeability tests for Doğanhisar clay.

Specimen	Curing time (day)	k (cm/s) (without freeze-thaw)	k (cm/s) (with freeze-thaw)	% Change of permeability
Without lime	0	5×10^{-9}	5×10^{-9}	0
%6 lime	1	1×10^{-6}	1×10^{-5}	900
%6 lime	3	5×10^{-6}	5×10^{-5}	900
%6 lime	7	6×10^{-6}	8×10^{-5}	12,333
%6 lime	21	7×10^{-6}	9×10^{-5}	11,857
%6 lime	28	8×10^{-6}	8×10^{-5}	900

Table 4: Unconfined compression test results for Aksaray and Doğanhisar clays treated with 6% lime.

Specimen	Curing time (day)	Unconfined compressive strength q_u (kN/m^2) (without freeze-thaw testing)	Unconfined compressive strength q_u (kN/m^2) (with freeze-thaw testing)	% Change of strength
Doğanhisar clay	1	428	375	123
	3	542	448	173
	7	623	562	98
	21	828	723	127
	28	995	902	93
Aksaray clay	1	548	461	159
	3	1138	989	131
	7	1676	1474	121
	21	3422	2856	165
	28	3878	3326	142

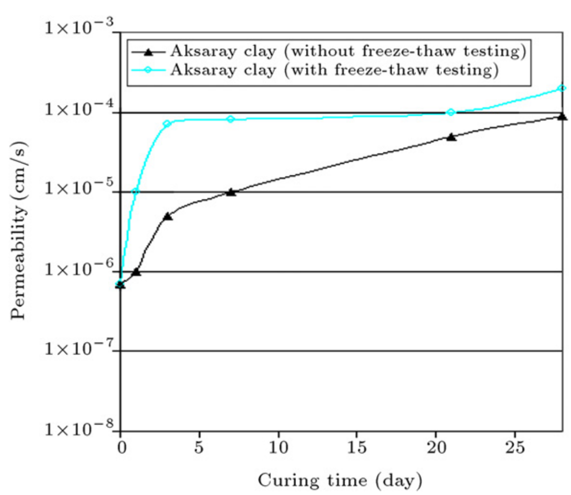

Figure 1: Permeability-curing time relationship for Aksaray clay treated with 6% lime.

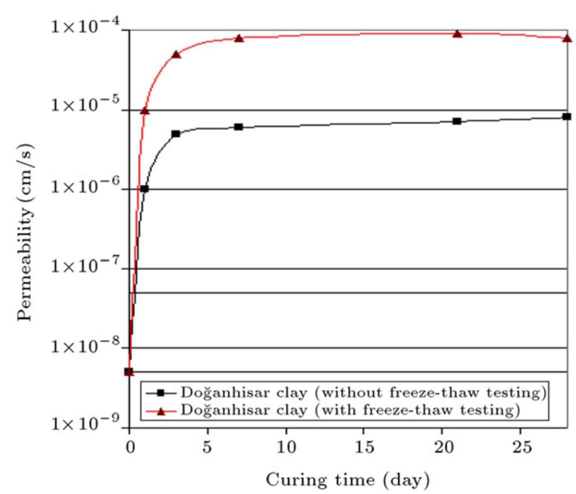

Figure 2: Permeability-curing time relationship for Doğanhisar clay treated with 6% lime.

Permeability-curing time relationships for Doğanhisar and Aksaray clays are plotted in Figures 1 and 2. The results of compressive stress–strain relationships for Doğanhisar and Aksaray clays are plotted in Figures 3–6. The effects of curing time and freeze-thaw are summarized in Table 4 for the two types of clay.

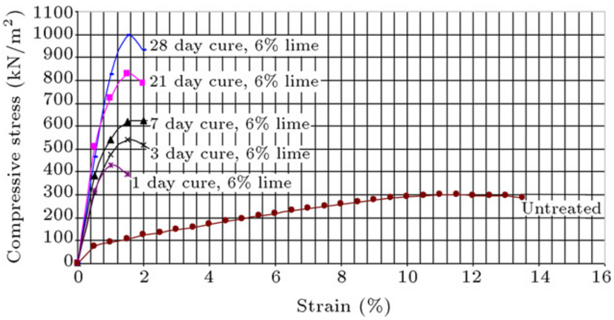

Figure 3: Compressive stress–strain relationship for Doğanhisar clay treated with 6% lime (without freeze-thaw testing).

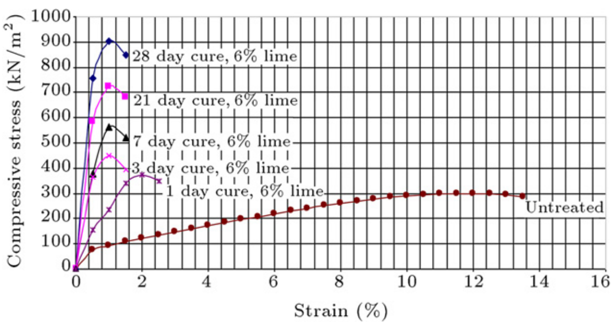

Figure 4: Compressive stress–strain relationship for Doğanhisar clay treated with 6% lime (with freeze-thaw testing).

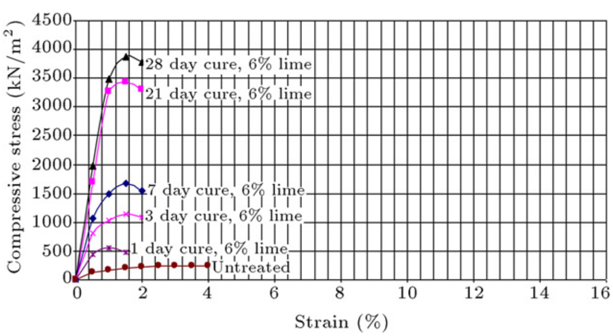

Figure 5: Compressive stress–strain relationship for Aksaray clay treated with 6% lime (without freeze-thaw testing).

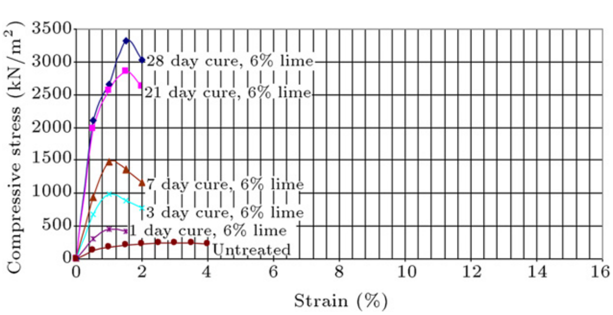

Figure 6: Compressive stress–strain relationship for Aksaray clay treated with 6% lime (with freeze-thaw testing).

5. Discussion of the results

1. Aksaray and Doğanhisar clays were mixed with 6% lime and compacted at optimum moisture content and cured for different periods. Some specimens were mixed with 6% lime and exposed to 3 freeze/thaw cycles (1 day freezing, 1 day thawing, 1 day freezing, 1 day thawing, 1 day freezing, 1 day thawing) and the changes of strength and permeability parameters of the specimens were measured.

2. This study has confirmed the theorem of increasing hydraulic conductivity by the effect of freeze-thaw cycles. For both clays, lime addition flocculated the clay soil particles and increased the value of the hydraulic conductivity of specimens 1000 times. These studies showed that the hydraulic conductivity of compacted clay increased by 10 to 20 times after only 3 freeze-thaw cycles. Numerous horizontal and vertical cracks formed during freeze-thaw. These cracks caused the increase of large hydraulic conductivities. Güler and Avcı [15] showed that the hydraulic conductivity value increased from 1.98×10^{-8} to 1.49×10^{-5} when 6% lime mixture was used. Daniels et al. [16] conducted an experimental investigation on the durability of natural and polymer-amended Boston Blue Clay used in waste containment applications. They observed that the hydraulic conductivity of this clay increased from 5×10^{-5} to 1×10^{-3} after five freeze-thaw cycles. The hydraulic conductivity for polymer-amended clay also increased in response to freeze-thaw cycling, however, both initial and final values were nearly an order of magnitude lower than those of natural clay. Chamberlain et al. [17] and Zimmie and La Plante [18] found that the freeze-thaw of compacted clay caused a 10–100 fold increase in hydraulic conductivity.

3. The unconfined compressive strength of the two clays exhibited different results. The strength of the high plasticity clay (Aksaray clay) increased approximately 15 times at the end of 28 day curing, while that of the low plasticity clay (Doğanhisar clay) increased approximately 3 times after the same curing period. The strength of two clays decreased 10% to 15% at the end of freeze-thaw cycles. Therefore, lime stabilization is more efficient on high plasticity clays because the strength of the Aksaray clay was more than that of the Doğanhisar clay at the end of curing times.

6. Conclusions

1. Calcium is the most important ingredient in the stabilization of clay. Lime provides calcium through the dissolution of calcium hydroxide in the presence of water.

2. Lime changes the properties of clay through a series of physiochemical modifications, including cation exchange, flocculation and agglomeration, and pozzolanic reaction.

3. Lime stabilization was more efficient on Aksaray clay. This effect could be justified by the high value of silica and calcium components (see Table 1).

4. The effect of freezing-thawing does not stop the pozzolanic reaction; however, it retards the reaction in the clay soil stabilized with lime. This situation shows that clay soils can be stabilized with lime in cold seasons.

5. Determining the levels of freezing effects of pozzolanic reactions occurring in two different clay types, having different plasticities and stabilized with lime, on permeability and strength is the significant objective of this study. In this study, differing from previous researchers, two types of clay having different pozzolanic reactions were used and compared with each other.

References

[1] Çinicioğlu, F.Ö. "İnce Taneli Zeminlerde Kireç veya Çimento Katkının Etkileri", *VI. National Clay Symposium*, İstanbul — Turkey, pp. 395–409 (in Turkish) (1993).

[2] Brandl, H. "Alteration of soil properties by stabilization with lime", *Proc., 10th International Conference on Soil Mechanics and Foundation Engineering*, 3, p. 587 (1981).

[3] Holtz, R.D. and Kovacs, W.D., *An Introduction to Geotechnical Engineering*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey pp. 356–360 (1981).
[4] Eades, J.L. and Grim, R.E. "Reaction of hydrated lime with pure clay minerals in soil stabilization", *Highway Research Board Bulletin*, 262, pp. 51–53 (1960).
[5] Chou, L. "Lime stabilization: reactions, properties, design, and construction", State of the Art Report 5, Transportation Research Board No. 7, National Research Council, Washington, DC, pp. 564–605 (1987).
[6] Chamberlain, E.J. and Gow, A.J. "Effect of freezing and thawing on the permeability and structure of soils", *Engineering Geology*, 13, pp. 73–92 (1979).
[7] Othman, M.A. and Benson, C.H. "Effects of freeze-thaw on the hydraulic conductivity of three compacted clays from Wisconsin", *Proceedings of 71st Annual Meeting, National Research Council*, Washington, DC, Transportation Research Record, No. 1369, pp. 118–125 (1993).
[8] Pousette, K., Macsik, J., Jacobsson, A., Andersson, R. and Lahtinen, P. "Peat soil samples stabilised in the laboratory — experiences from manufacturing and testing", In *Proceedings of the International Conference on Dry Mix Methods for Deep Soil Stabilisation*, Holm Brenderberg and Broms, Eds., pp. 85–92, Balkema, Rotterdam (1999).
[9] Thompson, M.R. and Dempsey, B.J. "Autogenous healing of lime soil mixture", Highway Research Board No. 263, pp. 21–25 (1969).
[10] ASTM D698-78A Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft3 600 kN-m/m^3).
[11] Daniel, D.E. and Benson, C.H. "Water content-density criteria for compacted soil liners", *Journal of Geotechnical Engineering ASCE*, 116(12), pp. 1811–1830 (1990).
[12] ASTM D5084 — 10 Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter.
[13] ASTM D560 — 03 Standard Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures.
[14] ASTM D2166 — 06 Standard Test Method for Unconfined Compressive Strength of Cohesive Soil.
[15] Güler, E. and Avci, C.B. "Kil Tabakalarının Permeabilitesine Kireç Stabilizasyonunun Etkisi", *VI. National Clay Symposium, İstanbul* — Turkey, pp. 209–216 (in Turkish) (1993).
[16] Daniels, J.L., Inyang, H.I. and Iskandar, I.K. "Durability of Boston clay in waste containment applications", *Journal of Materials in Civil Engineering*, 15(2), pp. 144–152 (2003).
[17] Chamberlain, E.J., Iskandar, I. and Hunsicker, S.E. "Effect of freeze thaw cycles on the permeability and macrostructure of soils", *Proc., Int. Symp. on Frozen Soil Impacts on Agric.*, Range and Forest Land, CRREL Special Report 90-1, US Army Corps of Engineers, Cold Regions Research & Engineering Laboratory, Hanover, NH, pp. 145–155 (1990).
[18] Zimmie, T.F. and La Plante, C. "The effects of freeze/thaw cycles on the permeability of a fine-grained soil", *Proc., 22nd Mid-Atlantic Industrial Waste Conf.*, Drexel Univ., Philadelphia, Pa, pp. 580–593 (1990).

Mustafa Yıldız received B.S., M.S. and Ph.D. Degrees in Civil Engineering, and Communication Systems Engineering in 1983, 1988, and 1998, respectively, from Selcuk University (SU), Turkey. His research interests include geotechnical engineering, and foundation engineering. He also studied as advisor to the Selcuk University Rector between 2005–2011. He has published many articles in the area of the geotechnical properties of clays.

Ali Sinan Soğancı received B.S., M.S. and Ph.D. Degrees in Civil Engineering in 2001, 2004, and 2011, respectively, from Selcuk University, Turkey. His research interests include geotechnical engineering and foundation engineering.