Lime-stabilisation of high plasticity swelling clay from Ethiopia

Worku Janka Negawo, Gemmina Di Emidio, Adam Bezuijen, R. Daniel Verastegui Flores & Bertrand François

Published online: 20 Mar 2017.

Submit your article to this journal ⧉

Article views: 37

View related articles ⧉

View Crossmark data ⧉

Taylor & Francis
Taylor & Francis Group

Check for updates

Lime-stabilisation of high plasticity swelling clay from Ethiopia

Worku Janka Negawo[a], Gemmina Di Emidio[b], Adam Bezuijen[b], R. Daniel Verastegui Flores[c]
and Bertrand François[d]

[a]Faculty of Engineering, Vrije Universiteit Brussel, Brussels, Belgium; [b]Laboratory of Geotechnics, Ghent University, Ghent, Belgium; [c]Institut of Mechanics, Material and Civil Engineering, Université Catholique de Louvain, Louvain-la-Neuve, Belgium; [d]Building, Architecture and Town Planning Department (BATir), Université Libre de Bruxelles, Brussels, Belgium

ABSTRACT

In the present study, highly expansive clay soils from the Highlands of Ethiopia were studied to evaluate the efficiency of lime treatment to improve their mechanical properties for road subgrades. Soils treated with quick lime at 5, 7 and 9% by dry weight of the soil were cured for seven days under controlled temperature of 40 ± 2 °C and geomechanical laboratory tests were conducted to evaluate its impact on the engineering properties of the soil. Test results show substantial improvements in the properties of the soil after lime treatment. Addition of lime significantly reduces the plasticity index and swelling potential of the soil. Similarly, despite the reduction of optimum proctor dry density due to lime treatment, the unconfined compressive strength and the California bearing ratio show considerable improvements. Based on the current study, expansive soils of the studied area can be effectively stabilised for road subgrade works with the addition of 7% quick lime by dry weight of the soil. For very problematic soil, as the one investigated here, the drastic reduction of swelling potential is of particular interest for a possible application of road subgrade.

1. Introduction

Expansive soils are extensively distributed throughout the world and often present considerable problems in civil engineering works (Shi, Jiang, Liu, & Fang, 2002). Especially, construction works as highway and lightweight structures face detrimental damages from this soil (Jones & Jefferson, 2012; Little, 1995; Nelson & Miller, 1992). In Ethiopia, over 13.8 million hectares of land is covered by expansive soils (MoARD, 2005). It represents 12.5% of the total land area. Its distribution is mainly concentrated in the highland and agriculturally fertile part of the country, which is the most densely populated part. As a result, expansive soil is a main source of concern in the construction of highways in the Highlands of Ethiopia where significant parts of that area is covered by this soil (Yitagesu, van der Meer, van der Werff, & Seged, 2011).

Expansive soils experience substantial changes in volume due to soil moisture content fluctuation. These soils swell when they get wet and shrink as they dry (Jones & Jefferson, 2012). These periodical changes in volume of soils result in differential settlement or heave of structures which leads to cracking and deformation of pavements and light structures. The swelling characteristics of expansive soil arise from the presence of swelling clay minerals. Soils that contain smectite clay minerals exhibit the largest swell shrink behaviour (Mitchell, 1976).

To avoid damages from expansive soils, a number of mechanisms can be implemented. Among these the major ones are removal and replacement, or stabilisation of the *in situ* soil material (Nelson & Miller, 1992). With regard to the first option, the costs related to transportation, material and waste disposal are usually very high. Moreover, this method has adverse environmental impacts. In many aspects, the stabilisation of *in situ* soil materials contributes both in the cost saving and ensuring environmental sustainability (Beckham & Hopkins, 1997; Little, Thompson, & Terrell, 1987).

The method of soil stabilisation involves the treatment of expansive soil with chemically reactive materials. This practice results in the improvement of soil engineering properties, such as physical and mechanical properties. Chemical soil stabilisation helps in altering soil consistency, grain size distribution, swelling properties and the mechanical strengths of the soils, such as unconfined compressive strength and California bearing ratio (CBR) (Little et al., 1987).

Nowadays, various chemicals are in use as soil stabilisers, including lime, cement and fly ash. The efficiency of these chemicals depends on the physical and chemical properties of the soil. These properties include soil plasticity, grain size distribution and the mineralogy of fine-grained soil particles. Soils that show high plasticity with higher proportion of fine-grained soil particles and containing smectite clay minerals can be effectively stabilised with lime (Bell, 1996). Whereas, soils with low plasticity and coarser grain sizes are commonly stabilised with cement or by the combination of cement and lime or fly ash (Little, 1995; Nelson & Miller, 1992). Consequently, lime is particularly well appropriated to treat efficiently high-plasticity expansive clays (Al-Mukhtar, Khattab, & Alcover, 2012; Al-Rawas, Hago, & Al-Sarmi, 2005; Mrabent, Hachichi, Souli, Taibi, & Fleureau, 2017; Nalbantoglu & Tuncer, 2001; Rao, Reddy, & Muttharam, 2001)

In recent years, extensive highway construction projects have been underway in the Highlands of Ethiopia. These areas are widely covered by expansive soils and the common mechanisms being implemented to deal with the problem of these soils has been through removal and replacement methods. Even though chemical soil stabilisation is widely practiced in many countries to deal with the problem of expansive soils, this practice appeared to be non-existent in developing countries, such as Ethiopia. In this study, we have looked at the potential of lime in stabilising expansive soils in the Highlands of Ethiopia to determine the feasibility of chemical soil stabilisation for future works. To accomplish this objective, laboratory soil tests on the physical, chemical and mechanical properties of soils collected from the area have been conducted.

2. Experimental methodology and materials

2.1. The study area

The study area is located in Central Ethiopia at a distance of 32 km south-east of Addis Ababa, the capital city of Ethiopia. The geographic coordinates of the study site is 8.88°N and 38.55°E and is situated in Dima rural community, in Sebeta Hawas district of Oromia regional state. The soil type of this area is predominantly Vertisols (expansive clayey soils) according to FAO soil classification system (MoARD, 2005). The elevation of the area is 2087 m asl and the general layout of the area consists of gentle slope plateaus and small valleys with seasonal streams.

2.2. Materials

The soil samples were taken from a depth of 50 to 150 cm after removing the top 50 cm of the surface soil. Sun dried soil samples were then treated with quick lime at four different dosages to determine the optimum lime requirement for stabilisation. The dosages of quick lime used were 0% (untreated soil), 5, 7 and 9% by dry weight of soil. The lime used in this study was quick lime manufactured at Ziway Caustic Soda S.C (Ethiopia), with a total oxide content (Ca and Mg) of about 91%.

Before each test was conducted, the quick lime was hydrated by water (32% by weight) based on the recommendation of National Lime Association of America (Little, 1995). To make the test specimens

for the lime treated soils, the mixture of soil and lime was first thoroughly mixed without adding water and then mixed again by adding the required amount of water in two steps dividing the water into two equal parts. The amount of added water to reach the targeted water content was determined by subtracting the residual water content, measured after sun drying. The same procedure was followed for mixing the untreated soil specimens in this case without the addition of lime (0% lime). All the tests on treated soils were performed after seven days of curing time at 40 °C. Our purpose is to evaluate the ability of the lime treatment to improve the mechanical properties at relatively short term that is the worst situation because the stabilisation process uses to improve the strength and stiffness with time. During curing, the samples have been sealed by double plastic film, in order to avoid any exchange of water with the environment.

A number of laboratory tests were performed for the classification of the soil and to determine the optimum lime requirement for its stabilisation. Specific methods adopted for the laboratory tests are presented as follows.

2.3. Determination of optimum lime requirement

Initially, the optimum lime requirement was determined based on Eades and Grim method (Eades & Grim, 1966). Based on this test, the optimum lime requirement was found to be 9%. As this amount appeared to be quite higher than most previous research findings (Al-Mukhtar, Lasledj, & Alcover, 2010a; Khattab, Al-Mukhtar, & Fleureau, 2007; Little, 1995), two more tests were also performed at lower lime dosages (5 and 7%).

2.4. Physical and chemical soil properties

The soil grain size analyses were performed following the procedures in *ASTM D 422* (1963/1998). Sedimentation tests were performed using 151H hydrometer.

The mineralogical characteristics of soil and soil-lime mixtures were examined using X-ray diffraction (XRD) analysis. The soil-lime mixtures used for UCS test (without soaking) were reused for the analyses of XRD. The specimen was prepared by air drying, grinding and then sieving.

Atterberg limits (liquid limit and plastic limit) tests were done following the procedures outlined in *ASTM D 4318* (1998). The samples were prepared based on the dry preparation method. For the determination of the liquid limit (LL), *Method A (multipoint test) procedure* was adopted using the Casagrande apparatus. The plastic limit (PL) test was performed on the material prepared for the liquid limit test following *hand method procedure*. Three repetitions for both limits were performed and the mean value was taken. The variability remained in acceptable limit as defined in the corresponding ASTM guidelines.

The optimum moisture content and maximum dry density of the untreated and lime treated soil specimens were determined in accordance with *ASTM D 1557* (1991/1998), *Modified Effort, Procedure C*.

2.5. Mechanical tests

The unconfined compressive strength (UCS) test was conducted based on *ASTM D 2166* (2000) and *ASTM D 5102* (1996) test methods. Two repetitions of each test were performed. Results does not differ more than 10% from each other. The specimens for the UCS test were prepared in a mould with a diameter of 36 mm and a height of 76 mm which results in a height to diameter ratio of 2.1. The compaction of soil sample for UCS test was done in three layers using impact action into the mould (*ASTM D 5102* [1996], *Procedure A*) at optimum moisture content to obtain the maximum dry density achieved based on *ASTM D 1557* (1991/1998).

The unconfined compressive strength of the specimen was measured under two conditions: with and without water soaking. Samples tested under soaking conditions were soaked in water for two days (48 h) before the test. During the soaking process, the specimens were wrapped in water permeable

tissue paper and placed on porous board which was in contact with water to allow capillary soaking (Little, 1995). The axial strain rate used for the UCS test was .4 mm min^{-1} (~.53% min^{-1}).

Soil sample preparation and compaction for CBR test were done as outlined in *ASTM D 1883* (2007) guidelines. The specimen was compacted to the maximum dry density at optimum moisture content as determined following the procedures in *ASTM D 1557* (1991/1998). After the curing period, the specimens were soaked under a surcharge load of 4.9 kPa in water bath for four days (96 h) to simulate the worst environment condition.

After the preparation of specimens for CBR and UCS tests, the specimens treated with quick lime were wrapped in air and moisture-tight plastic bags in double layers to avoid moisture loss and carbonation of the specimen. Then, the specimens were cured for seven days in a temperature controlled oven at 40 ± 2 °C. Curing of lime treated soil at 40 °C was used for accelerating the curing time. Under such a temperature, it is known that the pozzolanic reactions are accelerated (Al-Mukhtar, Lasledj, & Alcover, 2010b; George, Ponniah, & Little, 1992). During the curing period, water-soaked cloth was placed in the oven to maintain a high air humidity to avoid water loss from the specimens. The samples of lime treated soils for grain size analysis were taken from the post-failure soil in unconfined compression strength test (without soaking condition).

The swell potential test was conducted using CBR method. It was measured as the change in height of the specimen, expressed in percentage, during the soaking period of four days as stated above.

3. Results

3.1. Optimum lime requirement

Based on the method of Eades and Grim (1966), the optimum lime dosage for the stabilisation of the soil was determined to be 9%. This means the pH of soil-lime mixture solution attained 12.4 at 9% lime dosage. As it was mentioned above, this amount of lime appears to be higher than the values reported in previous studies done on similar soil type. As a result, stabilisation was also conducted at lower dosages of lime (i.e. 5 and 7%) to see if the improvement at lower lime content is practicable. The pH of soil-lime mixture solution is shown in Figure 1.

3.2. Changes in soil physical and chemical properties

This section presents the changes observed in the grain size distribution, liquid limit, plastic limit and moisture–density relationship up on compaction.

Soil grain size distribution of the studied soil was dominated by clay soil particles. About 80% by weight of the soil was in the clay fraction range and more than 99% of the soil was included in the
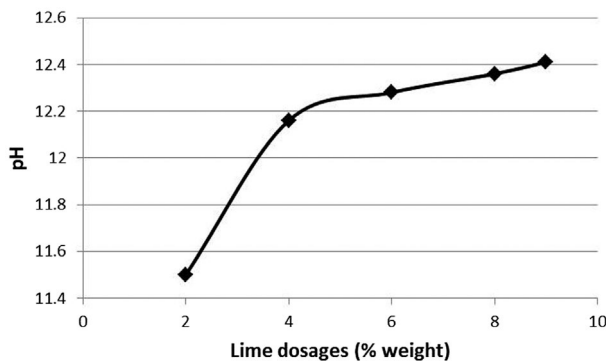

Figure 1. The pH of soil-lime mixture solution according to Eades and Grim method.
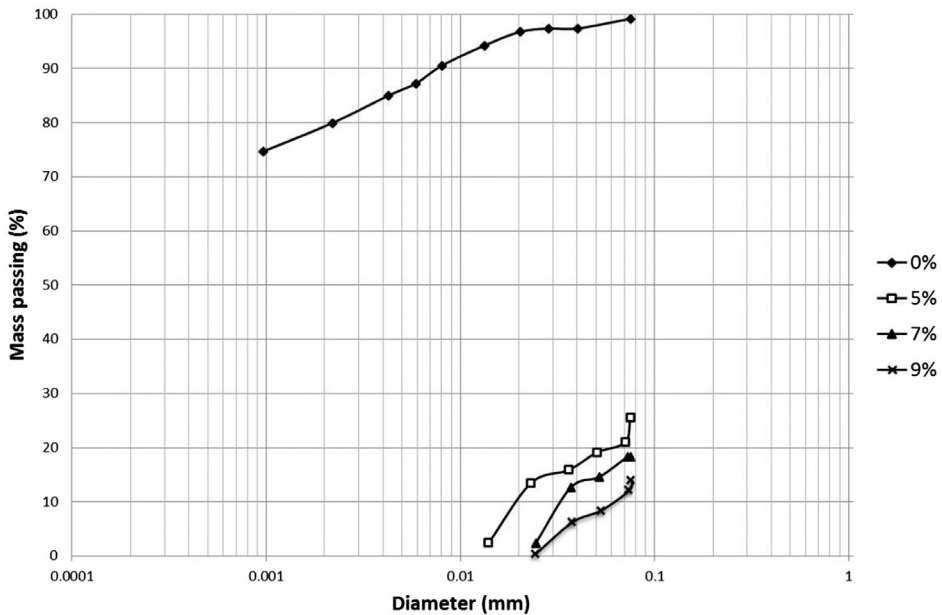
Figure 2. The distribution of fine-grained soils (<75 μm) for the lime treated and untreated soil samples (from sedimentation test).
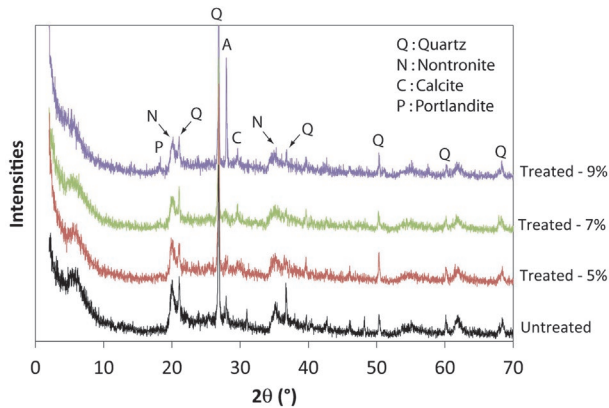

Figure 3. X-ray diffraction of untreated and treated soils with 5, 7 and 9% of lime content, after seven days of curing time. The curves have been shifted from each other for a better comparison.

fine soil particles (<75 μm). For lime treated soils, the fine fractions were considerably reduced due to particle aggregation. For the 5% lime treated specimen, the per cent of fines was only 25% by weight. For that of 7 and 9% lime dosages, the change in fine soil proportions was considerably high (Figure 2). Based on the wet sieving results, the maximum particle size of the soil specimens was found to be lower than 2 mm.

From the X-ray diffraction (XRD) analysis, the major mineralogical contents of the studied soil were quartz, nontronite and albite (Figure 3). For lime treated soils, portlandite was obtained in addition to quartz, nontronite and albite. For the case of 9% lime treated soil specimen, calcite ($CaCO_3$) was observed.

The liquid limit for the untreated soil sample was found to be about 104.4% and its plastic limit was 41.5% resulting in a plasticity index of 63%. The liquid limit and plastic limit could not be
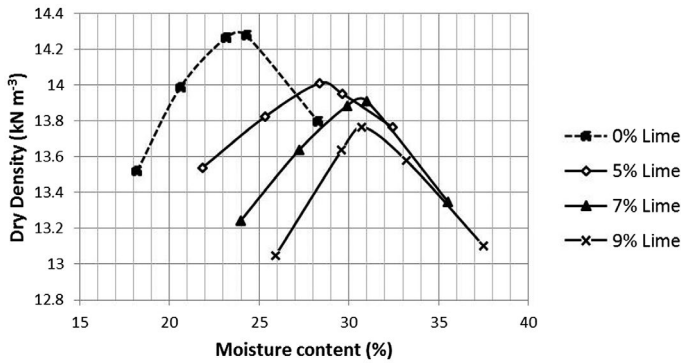
Figure 4. Moisture–density relationships upon compaction for lime treated and untreated soils.
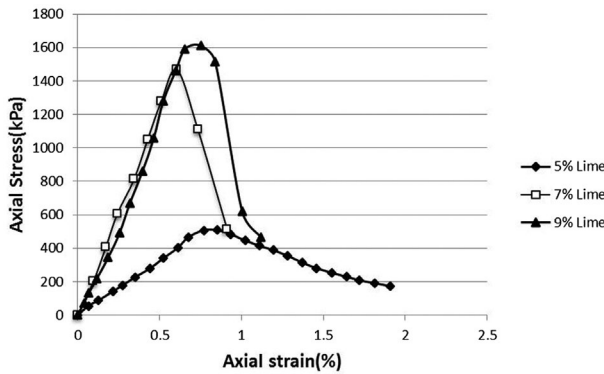

Figure 5. Stress–strain curves obtained during unconfined compressive tests on lime treated soils under soaked condition.

Table 1. Unconfined compressive strength of natural and lime treated soil, after seven days of curing time.

	Without water soaking		With water soaking	
Lime (%)	Strength at failure (kPa)	Strength gain (%)[a]	Strength at failure (kPa)	Change in strength (%)[b]
0	1438	– (Control)	~0	−100
5	1645	14	507	−69
7	1689	17	1469	−13
9	1799	25	1611	−10

[a]The gain in strength for all the treatments was calculated with respect to the UC strength of untreated soil without soaking scenario.
[b]The change in strength was calculated relative to the UC strength of the respective treatments without water soaking condition.

determined for the lime treated soil specimens as the materials became non-plastic. For the case of liquid limit, the groove closes for blows of less than 25 even for repeated number of trials. Similarly, the plastic limit was also not determined as the rod crumbles before reaching the recommended thickness of 3.2 mm.

The moisture–density relationship upon compaction for the lime treated and untreated soil sample is shown in Figure 4. The result shows a decreasing trend in maximum dry density as the lime content increases. Whereas, the optimum moisture contents show an increasing trend as the lime content increases.

Table 2. California bearing ratio of lime treated and untreated soils after a soaking period of four days (average of two tests).

Lime amount (%)	CBR value, at 2.54 mm (%)
0	.73
5	3.5
7	5.1
9	9

Table 3. The swell properties of lime treated and untreated soil specimens as obtained from CBR tests.

Lime (%)	CBR (swell, %)
0	8.1
5	1.3
7	1.2
9	.27

3.3. Unconfined compressive strength

The major purpose of the unconfined compression test is to obtain the compressive strength of cohesive soils. Table 1 shows unconfined compressive (UC) strengths of lime treated and untreated soil specimens under two conditions (with and without water soaking). In both scenarios, the results show an increasing trend in the UC strength as the level of lime added increases. For the condition without water soaking, the gain in UC strength from the addition of lime ranges from 14% for the 5% lime treated soil to 25% for the soil treated with 9% lime.

The strength gain due to lime treatment remains relatively moderate. As a result, additional UCS tests were performed on water-soaked specimens. For the case of water-soaked condition, there was a radical change in the strength of the untreated soil specimens (Table 1). The strength of the untreated soil was totally lost after water soaking. As a result, the UC strength of the untreated soil could not be accurately determined. Similarly, for the case of 5% lime treated soil, the strength loss was significant (i.e. more than two-third). Whereas, for the 7 and 9% lime treated specimens, the observed decrease in strength was only about 13 and 10%, respectively.

Figure 5 shows the stress–strain curves obtained during unconfined compression tests of lime treated soils under soaked conditions. The benefits of the lime treatment with 7 and 9% of lime are clearly evidenced with respect to a treatment with lower lime content (5%). The stiffness before failure and the ultimate strength are more than doubled when the treatment passes from 5 to 7% of lime. However, the post-peak response shows a brittle behaviour for the high contents of lime.

3.4. California bearing ratio

CBRs of lime treated and untreated soil sample after a soaking period of four days are shown in Table 2. The values are calculated at 2.54 mm (.1 in.) penetration. The CBR values show an increasing trend as the level of lime content increases for both penetration depths.

3.5. Swelling behaviour

As shown in Table 3, the swell potential measured from the CBR test for the lime treated soil was considerably low. Whereas, for the case of untreated soil specimen, the swell per cent observed was considerably high. The reduction of swelling potential between 7 and 9% of lime seems still effective even if the treatment with 5% of lime gives already acceptable results.

4. Discussion

4.1. Changes in physical properties

The flocculation of soil particles due to the lime treatment induces several changes to the physical properties of soil: (1) grain size distribution, (2) decrease of plasticity index, (3) decrease of density and increase of moisture content due to the presence of macropores.

From the result of grain size analysis, the studied soil falls in the category of clayey soil. However, upon treatment of the soil with a range of lime dosages, the grain size distribution of the soil shows significant change. This change was directly related to the amount of lime added. The change in grain sizes of soils can be attributed to the reaction that takes place between soil and lime particles which results into larger soil particles by a mechanism of flocculation. Since clay minerals and lime are highly reactive, chemical reactions undergo between these two mixtures resulting in the formation of new products such as calcium aluminate and calcium silicate minerals which help bond the mineral particles together (Le Runigo, Ferber, Cui, Cuisinier, & Deneele, 2011; Little, 1995).

From the moisture–density relationship tests, the optimum moisture content (OMC) for the untreated soil was observed to be considerably lower than that of lime treated soils. As compared to the untreated soil, the OMC of the lime treated soil specimens shows an increment ranging from about 19 to 29%. Similar results were also reported in other studies conducted on expansive soils (Amu, Adeyeri, Oduma, & Fayokun, 2008; Bell, 1996; Little, 1995). The reason for the rise in the OMC with lime content level could be due to the increase in the porosity of the soil due to the flocculation and agglomeration reactions between the soil and lime mixtures.

On the contrary, the addition of lime resulted in the reduction of the maximum dry density (MDD) of the specimens. The change in the MDD for the lime treated soil ranges approximately from 2 to 4% as compared to that of untreated soil. Similar trends were also reported in other studies (Amu et al., 2008; Bell, 1996; Tang, Vu, & Cui, 2011). The reason behind this could also be attributed to the increase in the porosity of the soil from the flocculation and agglomeration processes. These processes lead to an increase in the macropores of the soil in addition to the micropores that already exist resulting in the increase of the overall porosity of the soil.

4.2. Change in mechanical properties

The UCS test results for clay with different lime dosages for unsoaked specimens showed relatively low variations compared to specimen of water-soaked condition. Under water-soaked condition, significant differences were observed in the UCS of lime treated and untreated soils. Specimens treated with 0 and 5% lime showed considerable decrease in the UCS as compared to their values under unsoaked condition. These two treatments had also lost significant strength as compared to those specimens treated at 7 and 9% lime.

It appears that the amount of lime added at a rate of 5% may not be in sufficient amount to result in reactions that improve the soil strength to the required level. According to ASTM D 4609 (1994), a strength gain by 345 kPa or more due to chemical treatment as compared to the untreated sample may be considered effective. On the other hand, Thompson (1970) suggested a minimum requirement for UCS without soaking condition for sub-base material to be 689 kPa in no freeze-thaw activity zones and 1034 kPa for freeze-thaw zones. The UC strengths of all currently studied soils both untreated (without soaking) and lime treated specimens at 7 and 9% lime fulfil the criteria for subgrade and sub-base material according to the above requirements. However, as it was shown above, the UC strength is highly influenced by environmental conditions (saturation with water) at lower dosages of lime treatment or for untreated soil. It appears that the latter two recommendations may not be directly applicable to all conditions as it does not take the actual field condition into consideration. With regard to this issue, Little and Nair (2009) recommend that capillary soaking as the form of moisture conditioning should be performed before the unconfined compression test.

The CBR is extensively used in highway design and it is the measure for the penetration resistance of remoulded soil specimens (ERA, 2002; Nelson & Miller, 1992). In the application of this parameter in road design, various agencies have their own minimum requirement on the CBR value of materials. Normally, this value depends on the layer of the road to which the material is used, such as whether it is subgrade, sub-base or base material (ERA, 2002; Rogers, 2003). Based on the current study, the CBR value of the untreated soil was .73% and this does not fulfil the minimum required value for road subgrade (ERA, 2002). According to Asphalt Institute (Asphalt Institute, 1981), materials with a CBR value of less than 3% are considered poor material for sub-grade works. Similarly, the CBR result of soil treated with 5% lime was 3.5% and this also does not fulfil the minimum requirement of ERA (2002) for subgrade materials. According to Asphalt Institute, this material is grouped as moderate for subgrade application (Asphalt Institute, 1981).

On the other hand, the treatment of the soil with 7 and 9% lime resulted in better quality material for subgrade use. As a result, the CBR values of the treated soils at these rates of lime fulfil the minimum requirement of ERA (2002) for subgrade materials.

The other issue to be taken into consideration for the construction of light weight structures is the swell potential of the foundation soil. The observed swell potential of the studied soil was significantly high compared to the maximum requirements of various agencies (ERA, 2002; Nelson & Miller, 1992). However, the treatment of this soil with lime has considerably reduced the swell potential of the soil below the maximum requirement of those agencies. The significant decrease in the swell potential of the lime treated soil could be a result of various interactions between the soil-lime mixtures. The first reasons could be stabilisation of the smectite mineral by lime (decrease in diffuse double layer) and formation of less expansive minerals such as hydrated calcium alumino silicate thereby reducing the water holding capacity of the soil (Little, 1995; Sridharan & Jayadeva, 1982). The second cause for the decrease in the swell potential of the soil could be due to the cementing effect of lime on the soil particles (Kinuthia, 1997; Terrel, Epps, Barenberg, Mitchell, & Thompson, 1979).

5. Conclusion

The present study evaluated the effectiveness of lime to stabilise expansive soils for highway subgrade. The treatment of the soil with quick lime resulted in significant decrease in the plasticity and swell potential of the soil to the level that satisfies the requirement of different agencies for road subgrade application.

The UC strengths of lime treated soils under unsoaked condition showed only minor improvements as compared to untreated soil. However, saturation of the untreated soil with water resulted in significant decline in the compressive strength and this effect was also manifested in the samples treated with lower lime content (5%). On the other hand, the UC strengths of soils treated with 7 and 9% lime showed only a small decay under water saturation conditions. Moreover, the compressive strength of soils treated with 7 and 9% lime fulfil the minimum required value for highway subgrade material as perceived from various agencies' requirements.

Similarly, the CBR value of the soils treated with 7 and 9% quick lime were found to be in the allowable range for road subgrade material based on the requirements of highway construction agencies.

From the results of this study, it appears that the minimum amount of quick lime required for the effective stabilisation of the studied soil for road subgrade is about 7% based on the dry weight of the soil. The mild gain of resistance obtained by adding 2 more per cent of lime (from 7 to 9%) demonstrates that 7% is sufficient and that further addition of lime does not bring substantial additional benefits, at least for the performance after seven days of curing.

Acknowledgement

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Al-Mukhtar, M., Lasledj, A., & Alcover, J.-F. (2010a). Behaviour and mineralogy changes in lime-treated expansive soil at 20 °C. *Applied Clay Science, 50*, 191–198.

Al-Mukhtar, M., Lasledj, A., & Alcover, J.-F. (2010b). Behaviour and mineralogy changes in lime-treated expansive soil at 50 °C. *Applied Clay Science, 50*, 199–203.

Al-Mukhtar, M., Khattab, S., & Alcover, J. F. (2012). Microstructure and geotechnical properties of lime-treated expansive clayey soil. *Engineering Geology, 139*, 17–27.

Al-Rawas, A. A., Hago, A. W., & Al-Sarmi, H. (2005). Effect of lime, cement and Sarooj (artificial pozzolan) on the swelling potential of an expansive soil from Oman. *Building and Environment, 40*, 681–687.

Amu, O. O., Adeyeri, J. B., Oduma, E. W., & Fayokun, O. A. (2008). Stabilization characteristics of lime on palm kernel blended lateritic soil. *Trends in Applied Sciences Research, 3*, 182–188.

Asphalt Institute. (1981). *Asphalt pavement thickness design* (Information Series No. 181), AIIS181.

ASTM Standard D1557. (1991/1998). *Laboratory compaction characteristics of soil using modified effort*. West Conshohocken, PA: ASTM International. Retrieved from http://www.astm.org

ASTM Standard D1883. (2007). *CBR (California bearing ratio) of laboratory-compacted soils*. West Conshohocken, PA: ASTM International. Retrieved from www.astm.org

ASTM Standard D2166. (2000). *Unconfined compressive strength of cohesive soil*. West Conshohocken, PA: ASTM International. Retrieved from www.astm.org

ASTM Standard D422. (1963/1998). *Particle-size analysis of soils*. West Conshohocken, PA: ASTM International. Retrieved from http://www.astm.org

ASTM Standard D4318. (1998). *Liquid limit, plastic limit, and plasticity index of soils*. West Conshohocken, PA: ASTM International. Retrieved from www.astm.org

ASTM Standard D4609. (1994). *Evaluating effectiveness of chemicals for soil stabilization*. West Conshohocken, PA: ASTM International. Retrieved from www.astm.org

ASTM Standard D5102. (1996). *Unconfined compressive strength of compacted soil-lime mixtures*. West Conshohocken, PA: ASTM International. Retrieved from www.astm.org

Beckham, T. L., & Hopkins, T. C. (1997). *Stabilization of subgrade soil using hydrated lime product*. Kentucky: Kentucky Transportation Center.

Bell, F. G. (1996). Lime stabilization of clay minerals and soils. *Engineering Geology, 42*, 223–237.

Eades, J. L., & Grim, R. E. (1966). A quick test to determine lime requirements for lime stabilization. *Highway Research Record, 139*, 61–72.

ERA. (2002). *Sub-base, road base and gravel wearing course*. Addis Ababa: Ethiopian Roads Authority.

George, S. Z., Ponniah, D. A., & Little, J. A. (1992). Effect of temperature on lime-soil stabilization. *Construction and Building Materials, 6*, 247–252.

Jones, L. D., & Jefferson, I. (2012). Expansive soils. In J. Burland (Ed.), *ICE manual of geotechnical engineering* (Vol. 1, Geotechnical engineering principles, problematic soils and site investigation, pp. 413–441). London: ICE Publishing.

Khattab, S. A. A., Al-Mukhtar, M., & Fleureau, J. M. (2007). Long-term stability characteristics of a lime-treated plastic soil. *Journal of Materials in Civil Engineering, 19*, 358–366.

Kinuthia, J. M. (1997). *Property changes and mechanism in lime-stabilized kaolinite in the presence of metal sulphate* (PhD thesis). Pontypridd: University of Glamorgan.

Le Runigo, B., Ferber, V., Cui, Y. J., Cuisinier, O., & Deneele, D. (2011). Performance of lime-treated silty soil under long-term hydraulic conditions. *Engineering Geology, 118*, 20–28.

Little, D. N. (1995). *Handbook of stabilization of pavement subgrades and base courses with lime*. Prepared for APG Lime Company. Sponsored by the National Lime Association. Dubuque: Kendall/Hunt Publishing.

Little, D. N., & Nair, S. (2009). *Recommended practice for stabilization of subgrade soils and base materials*. Texas: National Cooperative Highway Research Program.

Little, D. N., Thompson, M., & Terrell, R. (1987). *Soil stabilization for roadways and airfields*. Florida, FL: Air Force Engineering and Services Center.

Mitchell, J. (1976). *Fundamentals of soil behavior*. New York, NY: Wiley.

MoARD. (2005). *Soil map of Ethiopia*. Addis Ababa: Ministry of Agriculture and Rural Development (Ethiopia).

Mrabent, S. A. B., Hachichi, A., Souli, H., Taibi, S., & Fleureau, J.-M. (2017). Effect of lime on some physical parameters of a natural expansive clay from Algeria. *European Journal of Environmental and Civil Engineering*, *21*, 108–125. doi: 10.1080/19648189.2015.1093963

Nalbantoglu, Z., & Tuncer, E. R. (2001). Compressibility and hydraulic conductivityof a chemically treated expansive clay. *Canadian Geotechnical Journal, 38*, 154–160.

Nelson, J. D., & Miller, D. J. (1992). *Expansive soils: Problems and practice in foundation and pavement engineering*. New York, NY: Wiley.

Rao, S. M., Reddy, B. V. V., & Muttharam, M. (2001). The impact of cyclic wetting and drying on the swelling behaviour of stabilized expansive soils. *Engineering Geology, 60*, 223–233.

Rogers, M. (2003). *Highway engineering*. Oxford: Blackwell Publishing.

Shi, B., Jiang, H., Liu, Z., & Fang, H. Y. (2002). Engineering geological characteristics of expansive soils in China. *Engineering Geology, 67*, 63–71.

Sridharan, A., & Jayadeva, M. S. (1982). Double layer theory and compressibility of clays. *Géotechnique, 32*, 133–144.

Tang, A. M., Vu, M. N., & Cui, Y.-J. (2011). Effects of the maximum soil aggregates size and cyclic wetting–drying on the stiffness of a lime-treated clayey soil. *Géotechnique, 61*, 421–429.

Terrel, R. L., Epps, J. A., Barenberg, E. J., Mitchell, J. K., & Thompson, M. R. (1979). *Soil stabilization in pavement structures-A user's manual volume 2: Mixture design considerations*.

Thompson, M. R. (1970). *Suggested method of mixture design procedures for limetreated soils*. New York, NY: American Society of Testing and Materials, Special Technical Publication.

Yitagesu, F. A., van der Meer, F., van der Werff, H., & Seged, H. (2011). Evaluation of soil expansion index from routinely determined geotechnical parameters. *Soil Science Society of American Journal, 75*, 1640–1651.