

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/260390246>

Strength behavior and microstructural characteristics of tropical laterite soil treated with sodium silicate-based liquid stabilizer

Article in *Environmental Earth Sciences* · July 2014

DOI: 10.1007/s12665-013-2939-1

CITATIONS

77

READS

2,541

3 authors, including:



Amin Eisazadeh

Sirindhorn International Institute of Technology (SIIT)

42 PUBLICATIONS 864 CITATIONS

[SEE PROFILE](#)



Aminaton Marto

Universiti Teknologi Malaysia

195 PUBLICATIONS 4,109 CITATIONS

[SEE PROFILE](#)

Some of the authors of this publication are also working on these related projects:



Geotechnical Behavior of soil dry bottom ash in dry wet condition [View project](#)



Soil stabilization for road subgrade [View project](#)

Strength behavior and microstructural characteristics of tropical laterite soil treated with sodium silicate-based liquid stabilizer

Nima Latifi · Amin Eisazadeh · Aminaton Marto

Received: 10 May 2013 / Accepted: 5 November 2013 / Published online: 20 November 2013
© Springer-Verlag Berlin Heidelberg 2013

Abstract Although the effects of nontraditional stabilizers on the geotechnical properties of tropical soils has been the issue of investigation in recent years, the microstructural characteristics of nontraditional soil additives and in particular selected additive (TX-85) have not been fully studied. Nontraditional soil stabilization additives are widely used for stabilizing marginal materials. These additives are low-cost alternatives to traditional construction materials and have different compositions. They also differ from one another while interacting with soil. In line with that, it was the objective of this research to investigate the strength properties and physicochemical mechanisms related to tropical laterite soil mixed with the liquid stabilizer TX-85. Macro-structure study, i.e., compaction, and unconfined compression strength test were used to assess the engineering and shear properties of the stabilized laterite soil. In addition, the possible mechanisms that contributed to the stabilization process were discussed using various spectroscopic and microscopic techniques such as X-ray diffractometry (XRD), energy-dispersive X-ray spectrometry, scanning electron microscopy, and Fourier transform infrared spectroscopy. From engineering point of view, the results indicated that the strength of TX-85 stabilized laterite soil improved significantly. The degree of improvement was approximately four times stronger than natural soil after a 7-day curing period. The XRD showed no crystalline products (gel form). Moreover, weathering effects were obvious in TX-85 treated

samples in most of clay minerals' peak intensities. These effects were reduced especially for kaolinite mineral inside the soil with curing time.

Keywords Laterite soil · Non-traditional additives · Sodium silicate · UCS · SEM · FTIR

Introduction

In recent years, increasing population and rapid development of construction industry necessitate acquiring sufficient knowledge and information about methods of improving current soil surfaces for geotechnical applications. Nowadays, among the different methods of soil improvement, chemical soil stabilizers are commonly used to increase the soil strength and workability. Soil stabilization is the process of improving the physical and engineering properties of soil to obtain some predetermined targets. This popularity is due to their low cost and convenience, particularly in the geotechnical projects that require a high volume of soil. However, it should be noted that each type of stabilizer is suitable for a specific type of soil and climate. There have been noticeable important dissimilarities between tropical soils from the more ordinary soils of moderate climates. Rock weathering in these areas is very rigorous that can be described by fast disintegration of feldspars as well as ferromagnesian raw materials, the displacement of bases including Na_2O , K_2O , and MgO and silica, and the absorption of aluminum and iron oxides (Mitchell and Soga 2005). This procedure which includes leakage of silica and decomposition of iron and aluminum oxides is called laterization (Gidigas 1972). In misty regions, Laterite can be considered as a soil type rather than a properly-explained resource. In these

N. Latifi (✉) · A. Eisazadeh · A. Marto
Geotechnic & Transportation Department, Faculty of Civil
Engineering, Universiti Teknologi Malaysia, 81310 UTM
Skudai, Johor, Malaysia
e-mail: en_latifi@yahoo.com

regions, dense rainfall in presence of efficient drainage systems and warm temperatures develop substantial layers of lateritic soil group with reddish color. This soil category is affluent in aluminum, iron, and kaolinite clays (Townsend 1985). The existence of iron oxides makes the color of laterite soils red, beginning from light through bright to brown shades (Syafalni et al. 2012).

The stabilizers of soils are categorized into two main groups as traditional and nontraditional stabilizers (Eisazadeh 2010). Traditional stabilizers such as cement, lime, fly ash, and bituminous materials are widely studied, and their essential stabilization techniques have been recognized (Kassim and Chow 2000; Kassim et al. 2005; Hafez et al. 2008; Eisazadeh et al. 2011). A number of nontraditional soil stabilizer products which are not calcium based are potentially effective alternatives for treating soils. These nontraditional chemical stabilizers are usually sold as concentrated liquids diluted with water at the construction site, then either spread on the soil before compaction or pressure injected to treat deeper soil layers. However, nontraditional additives comprise of many different chemical agents that are varied in their components and in the manner they react with the soil. Regrettably, not much has been reported about their reaction with geotechnical resources or their basic stabilization mechanisms. As a result of the proprietary character of the viable stabilization additives, their precise chemical components are not revealed. Hence, contrary to the traditional stabilizers, efforts to explain the strengthening mechanisms of nontraditional stabilizers have been hindered.

The majority of laboratory and field testing with nontraditional stabilizers have relied on performance evaluation rather than mechanism recognition. There are comparatively few studies regarding stabilization mechanisms of nontraditional additives. As reported in previous studies, the scanning electron microscopy (SEM), energy-dispersive X-ray spectrometry (EDAX), X-ray diffractometry (XRD), and Fourier transform infrared spectroscopy (FTIR) tests have been useful for micro-structure study of soil mixed with different type of stabilizers (Eisazadeh et al. 2011). The result of previous study indicated that the nontraditional liquid additives can help to increase soil strength with curing time (Santoni et al. 2002, 2005; Tingle and Santoni 2003; Marasteanu et al. 2005; Zhu and Liu 2008; Fon 2010; Ou et al. 2011; Liu et al. 2011; Ali 2012; Marto et al. 2013). It should be noted that, each type of additives have different influence and mechanism on soil stabilization. For example, the literature showed that the ionic stabilizers increase the strength of soil by cationic exchange and flocculation, Enzymes by organic molecule encapsulation, Polymers by physical bonding and cementation, and salts by hygroscopy, cation exchange, and flocculation or crystallization and cementation (Scholen

1995; Tingle and Santoni 2003; Eisazadeh 2010; Liu et al. 2011; Ojuri and Ogundipe 2012; Solanki and Zaman 2012).

It was important to carry out a complete survey to fully understand the microstructure and mineralogy of soil stabilized with selected stabilizer TX-85. In this paper an effort was made to recognize the mechanisms responsible for the enhancement of laterite soil stabilized with the domestic liquid additive. The engineering properties of untreated and treated soil, i.e., unconfined compression strength (UCS) and compaction were monitored with curing time. Furthermore, the possible mechanisms that contributed to the stabilization process were discussed based on the results obtained from the microscopic and spectroscopic techniques involving XRD, SEM, EDAX, and FTIR.

Materials and experimental program

Materials

This study was conducted on residual laterite soil that is usually found in tropical areas. The color of this clayey soil is reddish due to high amount of iron oxides. Tables 1 and 2 presents the physical and chemical properties of this soil, respectively. The liquid stabilizer was sold with the commercial name ‘TX-85’ by the Probase factory located in Johor province of Malaysia. The exact chemical composition of this stabilizer has not been released yet, since it is a commercially registered brand. The result of inductively

Table 1 Characteristics of the natural laterite soil

Engineering and physical properties	Values
pH (L/S = 2.5)	5.35
Specific gravity	2.69
External surface area (m ² g ⁻¹)	41.96
Liquid limit (LL) (%)	75
Plastic limit (PL) (%)	41
Plasticity index (PI) (%)	34
BS classification	MH
Maximum dry density (mg m ⁻³)	1.31
Optimum moisture content (%)	34
Unconfined compressive strength (kPa)	270

Table 2 Oxides and chemical composition of laterite soil

Chemical composition (oxides)	Values (%)
SiO ₂	25.46
Al ₂ O ₃	31.10
Fe ₂ O ₃	35.53
CO ₂	7.91

coupled plasma mass spectrometry (ICP-MS) performed on the liquid stabilizer indicated that Na, Al, Si, and Fe were the major elements present. Also the pH value (12.54) of TX-85 revealed its highly alkaline nature.

Sample preparation

The results of laboratory studies of Eisazadeh (2010) on the laterite soils revealed significant changes in their compaction properties due to oven drying. In order to avoid the mentioned changes, air-drying method was used for all soil specimens. The specimens were sieved by a 2 mm mesh to confirm the uniformity of the soil. In order to prepare various mix designs, a standard protocol was used. The first step was conducted based on clause 3.3.4.2 of BS 1377: Part 4: British Standards Institution (1990a). This step included the determination of the optimum moisture content (OMC) for natural soil and soils mixed with different amount of stabilizer. In the second step, specified amount of stabilizer was added to water and mixed with the soil. In order to prepare a homogeneous mix, irregular hand mixing with palette knives was done. Then after, the target dry density and moisture content were reached by compressing the samples in a steel cylindrical mold fitted with a collar that accommodated all the mixtures. The required compaction was done by a hydraulic jack using persistent compaction based on clause 4.1.5 of BS 1924: Part 2: British Standards Institution (1990b). Finally, the cylindrical samples were extruded using a steel plunger, trimmed, cleaned of releasing oil and placed in a plastic bottle and wrapped in several runs of cling film. These samples were cured for 3, 7, 14, 28, and 90 days in a 27 ± 2 °C temperature controlled room (Zhang et al. 2012). In order to simplify the presentation of results, a specimen designation scheme was employed. The first and second characters indicated the soil name and type of treatment, respectively. The other characters included LC for laterite clay, UNT for untreated, LST for liquid stabilizer treated, and D for days.

Testing program

The general characterization studies of the present investigation are categorized into macro-structure characteristic and micro-structural analyses. A standard compaction test was employed to define the compaction properties of the natural soil and soil mixed with different amount of stabilizer based on BS 1377: Part 4: British Standards Institution (1990a, b) (clause 3.3.4.1). This was achieved by compacting the soil into a 1L Proctor mold by applying 27 blows of a 2.5 kg circular faced (50 mm diameter) hammer on each of the three equal layers. Then based on the moisture-density relationship curve obtained for each mix

design, the OMC and its corresponding dry density were determined. In order to find the optimum amount of liquid stabilizer, five concentrations of diluted additive, i.e., 3, 6, 9, 12, and 15 % of dry weight of soil were used in preparing mix designs. The untreated soil specimen was also used as a control sample. These samples were made by OMC and 90 % of maximum dry density (Ahmad 2004). The soil improvement index was determined by conducting serious of UCS test (BS 1924: Part 2: British Standards Institution 1990a, b) on multiple specimens at different time intervals. A rate of axial strength equal to 1 % per minute was applied to the samples. The acquisition data unit (ADU) was used to record the applied load and axial deformation automatically. The failure of each specimen was defined by its peak axial stress. The failed specimens were dried and weighted in the end of each test to calculate their moisture content.

In the present study, XRD technique was used to achieve two goals: first, involving the measurement of mineralogical changes of soil structure due to the presence of liquid stabilizer, and secondly, to find newly formed crystalline cementitious compounds. A Bruker D8 advance diffractometer was employed for the analysis of cured samples. The Cu-K α radiation ($k = 1.54$ Å) at an angle scan (2θ) of 6–90°, step size of 0.02°, and 1 s lodging at each step was used for scanning. The high resolution images of fabric of the soil prior and after the treatment were captured by a SEM that was equipped with EDAX. In order to prepare the samples, they were completely covered by platinum under highly vacuum environment. Moreover, the EDAX method was used to find the major elemental composition on the surface of treated particles. The results were presented based on the ratios of Al:Si and Na:Si at varying time intervals. The analysis of FTIR was applied on treated samples to determine their molecular structural changes. In order to measure the absorption bands of the prepared KBr disk, a 2 mg sample of grounded dried soil was mixed with 200 mg KBr. The sample was scanned by a Perkin Elmer Spectrum 2000 gadget in the 400–4,000 cm^{-1} infrared spectrum range.

Results and discussion

The main aim of compaction is to maximize soil density. The soil compaction properties can significantly be changed by adding a single anion or cation introduced by the stabilizers. Therefore, it is rational to suggest that soil-stabilizer reactions are affected by the initial compactive effort, since this had direct influence on the particle spacing and the subsequent crystallization process. Compaction tests were performed on pure laterite soil and the soil mixed with 3, 6, 9, 12, and 15 % liquid stabilizer (TX-85).

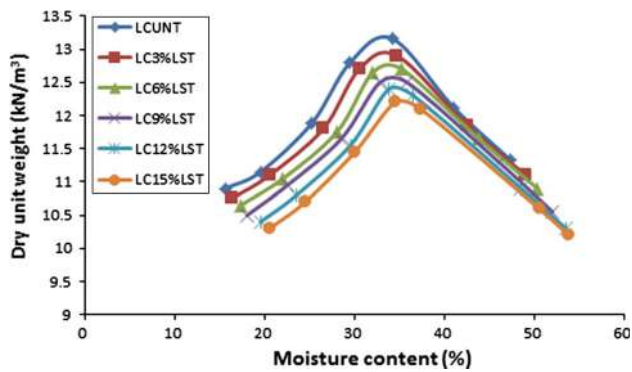


Fig. 1 Result of the compaction test on laterite soil, and mixed with different percentage of TX-85

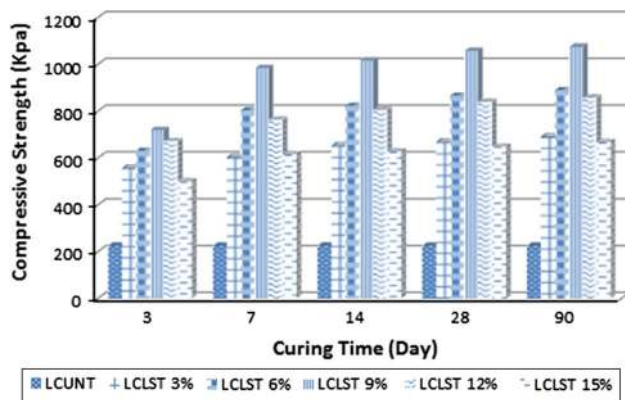


Fig. 2 Strength gained for TX-85 treated laterite soil with different stabilizer content and curing time

As can be seen in Fig. 1, adding TX-85 into the laterite soil reduced the dry density and increased the OMC for the same compactive effort, however, the amount of observed changes was rather small. This decrease in the dry density can be due to the particle flocculation and agglomeration caused by the rapid cation exchange in the soil-stabilizer mixture. Also, the increase of the moisture content was probably because of the rapid and exothermic nature of the reaction between soil and additive which led to loss of

water. The data obtained was in good agreement with the results reported by Sukmak et al. (2013a) which studied the stabilization behavior of silty clay soil (a mixture of soil, fly ash, sodium silicate solution, and sodium hydroxide solution). It should be added that the less noticeable changes observed in the OMC of stabilized soil could have been due to the fact that in low swelling silty clays the OMC is mainly controlled by the liquid limit (Horpiulsuk et al. 2009).

Figure 2 shows the results of UCS tests of stabilized mixtures for different time intervals. Apparently, a significant increase in the strength properties of the natural soil was occurred due to the TX-85 treatment. The enhancement in the compressive strength of 9 % TX-85 treated samples was 984 kPa after 7 days curing. This was approximately four times greater than the untreated soil strength and was gained much faster in comparison to other liquid type stabilizers such as phosphoric acid which required an 8 months curing period to achieve a 800 kPa compressive strength (Eisazadeh 2010). It could be noted that the rate of strength increment was rather limited after 7 days curing period which reached a value of 1,075 kPa after 90 days cured samples. This indicated that most part of the soil-stabilizer reactions happened within the first 7 days. On the other hand, it was clear that for the samples treated with higher liquid stabilizer content (more than 9 % TX-85) a lower compressive strength was achieved. The latter was probably due to the increase in the positive surcharge and the subsequent repulsion of soil particles inside the mixture (Eisazadeh 2010; Tingle and Santoni 2003; Katz et al. 2001; Rauch et al. 2002; Tingle et al. 2007). The degradation of strength could also have been due to the amount of alkaline stabilizer (pH value = 12.54) which exceeded the requirement for chemical reaction in the samples (Sukmak et al. 2013b). Hence, based on the obtained results, 9 % of TX-85 was chosen as the optimum value that was added to the laterite soil for micro-structural studies.

Figure 3 shows the XRD patterns for natural and chemically treated laterite soil. A comparison was made

Fig. 3 XRD patterns for the natural and TX-85 treated samples with different curing time

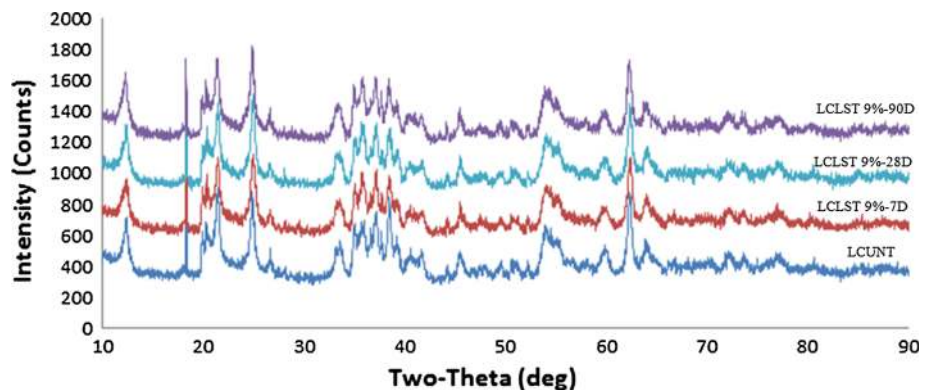
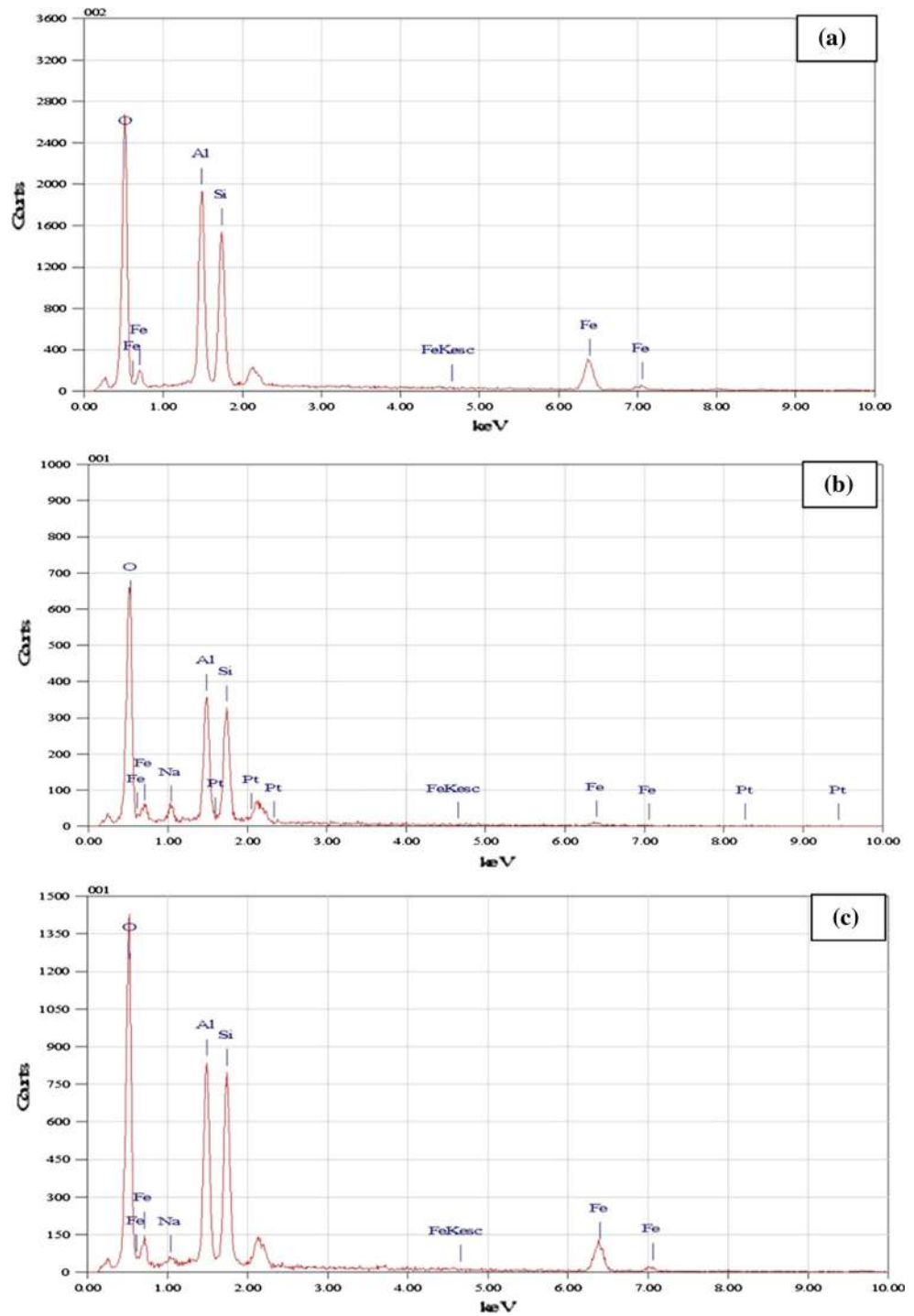


Fig. 4 EDAX spectrums of **a** untreated laterite soil, **b** 9 % TX-85 treated laterite soil after 7 days, and **c** 9 % TX-85 treated laterite soil after 90 days



between the resultant patterns and the standard dataset from Joint Committee for Powder Diffraction Standards (JCPDS 1995). The main existed minerals in the laterite clay specimens were kaolinite ($2\theta = 12.5^\circ, 20^\circ, 35^\circ, 38^\circ, 46^\circ, 55^\circ$), quartz ($2\theta = 27^\circ, 36.5^\circ, 42.5^\circ, 50^\circ$), geothite ($2\theta = 21.5^\circ, 36.5^\circ, 41^\circ, 53^\circ$), and gibbsite ($2\theta = 18.5^\circ, 20^\circ, 27^\circ, 38^\circ$) (Brown 1961; Ahmad 2004; Eisazadeh

2010). Comparisons of the XRD results for the treated and untreated samples in Fig. 3 showed that quartz was unaffected by the treatment. However, there was a noticeable change in the XRD results for the kaolinite spectra. Generally, in all of the treated samples, few peaks were diminished and reduced slightly. This was because of the stabilizer effect and its weathering action on the clay

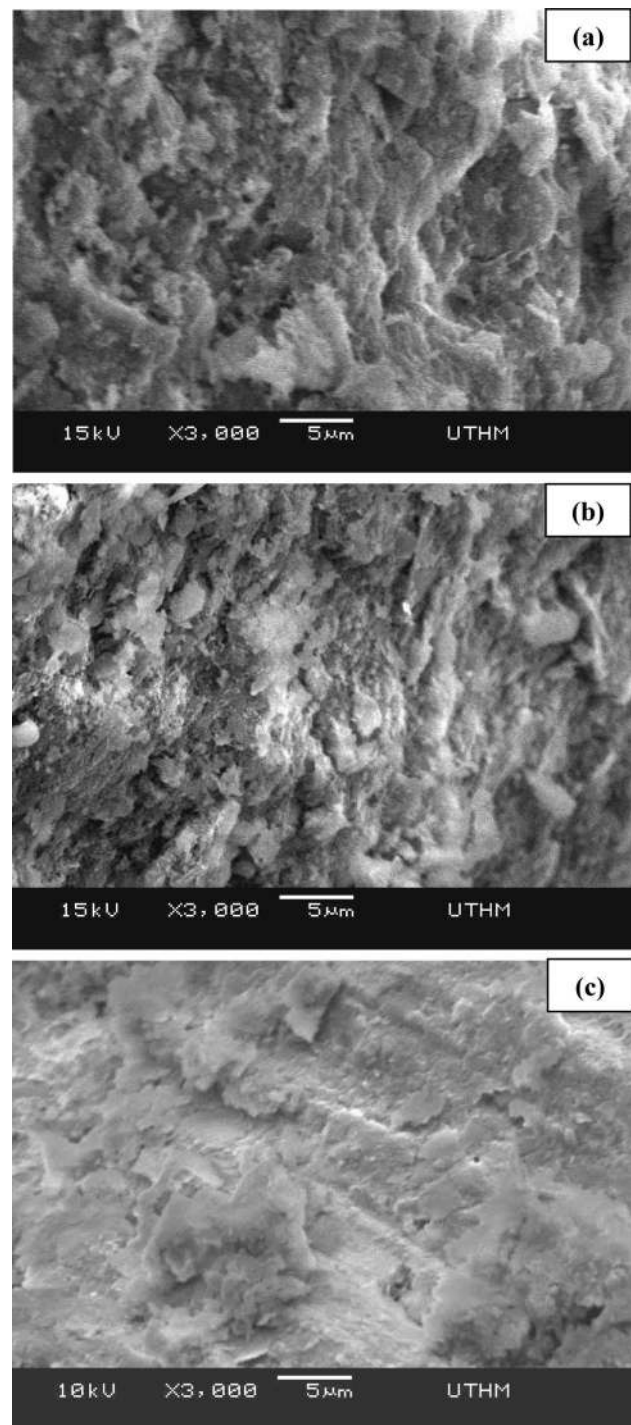
Table 3 Al:Si and Na:Si ratios of 9 % TX-85 and various curing time obtained from EDAX analysis

LCUNT	LCLST9 %-7D	LCLST9 %-28D	LCLST9 %-90D
Al/Si = 1.17	Al/Si = 0.93	Al/Si = 0.89	Al/Si = 0.91
Na/Si = 0	Na/Si = 0.14	Na/Si = 0.07	Na/Si = 0.03

minerals. However, no new peaks due to the gel-form (amorphous) structure of formed reaction products were obtained (Katz et al. 2001; Tingle et al. 2007; Fernandez et al. 2011; Brough and Atkinson 2002).

In order to better understand the surface composition of treated particles, EDAX analysis was performed on cured samples. Figure 4a–c represents the EDAX spectrums of the natural laterite soil and the treated soil with 9 % TX-85. The time-dependent variations in the ratios of Al:Si and Na:Si for different mix designs is shown in Table 3. Comparison of the results revealed a noticeable change in the surface composition of clay particles after treatment. Micro-analyses of the treated samples in the SEM were also performed at different time intervals. Figure 5a–c present the SEM results of untreated and treated soil samples. The existence of free oxides within the untreated soil (LCUNT) covered and bonded the soil particles together in a big packet fabric. On the other hand, the formation of new white layers of reaction products on the surface of clay particles in 90 days cured samples (Fig. 5c) was evident. It should be noted that by means of an energy dispersive X-ray spectrometer (EDAX), these compounds were roughly identified as sodium aluminosilicate hydrate (N–A–S–H) (Brough and Atkinson 2002; Fernandez et al. 2011; Rajasekaran and NarasimhaRao 1997; Cai et al. 2006; Eisazadeh et al. 2011; Tingle et al. 2007; Katz et al. 2001; GarcíaLodeiro et al. 2009).

The FTIR analysis is used to measure the absorption bands at characteristic wavelengths of bonds that vibrate independently of one another in order to define the functional groups of soil minerals. Figure 6 shows the FTIR spectrums for the natural and chemically stabilized samples. The common features of FTIR spectrums involved the followings: the bands at 1,111 and 1,028 cm^{-1} indicated the perpendicular and in-plane Si–O stretching, respectively. The peaks at 3,615 cm^{-1} corresponded to inner OH-stretching vibrations and band at 3,692 cm^{-1} was inner-surface hydroxyl groups (Eisazadeh et al. 2011). The latter was a typical band of kaolinite mineral, while the former was a characteristic of various phyllosilicate minerals. Moreover, the band at 910 and 792 cm^{-1} indicated the existence of hematite, respectively (Gadsen 1975) and quartz (Marel and Beutelspacher 1976). The other bands including the Si–O vibrations observed at 535, and 466 cm^{-1} mostly defined the

**Fig. 5** SEM images of **a** untreated laterite soil, **b** 9 % TX-85 treated laterite soil after 7 days, and **c** 9 % TX-85 treated laterite soil after 90 days

existence of kaolinite mineral. A stretching vibration was identified at 3,446 cm^{-1} , while the 1,637 cm^{-1} band was an H–O–H flexible band of water with an overtone happening at 3,378 cm^{-1} . The results of FTIR spectrum for 7, 28, and 90 days cured samples confirmed that the chemical

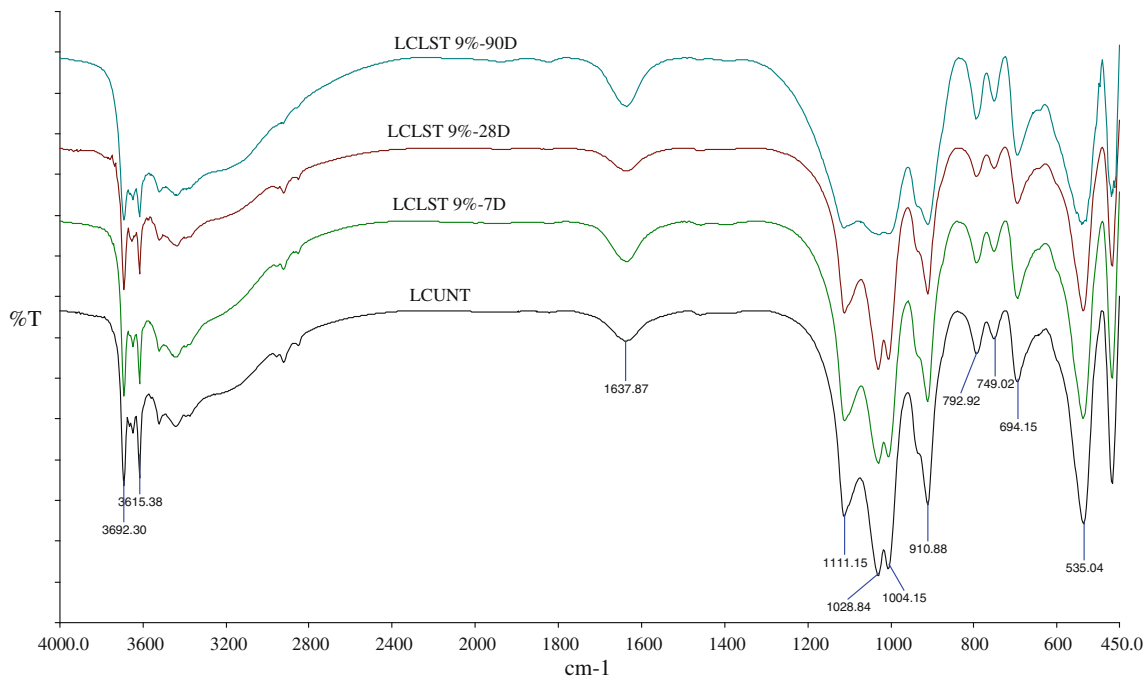


Fig. 6 FTIR spectrums for untreated and TX-85-treated laterite soil with different curing time

treatment was able to make a noticeable difference in the Si–O functional groups of soil particles. Also, in general the peaks intensities reduced with curing time. This was because of the weathering action of the stabilizer on the clay minerals (Nacamoto 1970; Eisazadeh et al. 2011; Phair and Van Deventer 2002; García-Lodeiro et al. 2008; Eisazadeh et al. 2012).

Conclusion

In this paper, different analytical technique related to the strength behavior and micro-structural characteristics of laterite soil treated with sodium silicate-based liquid stabilizer was studied. The main aim was to understand the mechanisms that accelerated the stabilization process. The UCS data for various mix designs indicated a significant and rapid (7 days) strength improvement for the selected nontraditional stabilizer. Also, it was found that for the samples treated with higher liquid stabilizer content (more than 9 % TX-85) a lower compressive strength was achieved. The latter was probably due to the increase in the positive surcharge and the subsequent repulsion of soil particles inside the mixture. Hence, 9 % of TX-85 was chosen as the optimum value that was added to the laterite soil for micro-structural studies. Based on the SEM and EDAX results the new formed gel-like cementitious compounds of sodium aluminosilicate hydrate (N–A–S–H) were believed to be the main cause of strength

development. The XRD results also revealed a general reduction in the clay mineral peaks with curing time. However, no new peaks due to the gel-form (amorphous) structure of formed reaction products were obtained. The results of FTIR spectrum for different curing periods indicated few noticeable changes in the Si–O functional groups of soil particles. Also, in general the peaks intensities reduced with curing time. This was because of the weathering action of the stabilizer on the clay minerals.

Acknowledgments Research university grants (Vot. 05J77 & 05J79) from Universiti Teknologi Malaysia and Ministry of Higher Education (MOHE) Malaysia are gratefully acknowledged.

References

Ahmad K (2004) Improvement of a tropical residual soil by electrokinetic process. Doctoral dissertation, Universiti Teknologi Malaysia, Faculty of Civil Engineering
 Ali F (2012) Stabilization of residual soils using liquid chemical. *Electron J Geotech Eng (EJGE)* 17:115–126
 British Standards Institution (1990a) British standard methods of test for soils for civil engineering purposes: part 4, Compaction-related tests. London, BS1377
 British Standards Institution (1990b) British standard methods of test for soils for civil engineering purposes: part 2. Classification tests. London, BS1377
 Brough AR, Atkinson A (2002) Sodium silicate-based, alkali-activated slag mortars: part I. Strength, hydration and micro-structure. *Cem Concr Res* 32(6):865–879
 Brown G (1961) The X-ray identification and crystal structures of clay mineral. Mineralogical society (Clay Minerals Group), London

- Cai Y, Shi B, Ng CW, Tang CS (2006) Effect of polypropylene fibre and lime admixture on engineering properties of clayey soil. *Eng Geol* 87(3):230–240
- Eisazadeh A (2010) Physicochemical behavior of lime and phosphoric acid stabilized clayey soil. Doctoral dissertation, Universiti Teknologi Malaysia, Faculty of Civil Engineering)
- Eisazadeh A, Kassim KA, Nur H (2011) Characterization of phosphoric acid-and lime-stabilized tropical lateritic clay. *Environ Earth Sci* 63(5):1057–1066
- Eisazadeh A, Kassim KA, Nur H (2012) Solid-state NMR and FTIR studies of lime stabilized montmorillonitic and lateritic clays. *Appl Clay Sci* 67:5–10
- Fernandez A, Vazquez T, Palomo A (2011) Effect of sodium silicate on calcium aluminate cement hydration in highly alkaline media: a microstructural characterization. *Am Ceram Soc* 94(4):1297–1303
- Fon CL (2010) Stabilization of earth roadbed for road building using probase soil stabilizer. *Electron J Geotech Eng (EJGE)* 15:1793–1814
- Gadsen JA (1975) Infrared spectra of minerals and related inorganic compounds. Butterworths, London
- GarcíaLodeiro I, Macphée DE, Palomo A, Fernández-Jiménez A (2009) Effect of alkalis on fresh C–S–H gels. FTIR analysis. *Cem Concr Res* 39(3):147–153
- García-Lodeiro I, Fernández-Jiménez A, Blanco MT, Palomo A (2008) FTIR study of the sol–gel synthesis of cementitious gels: C–S–H and N–A–S–H. *J Sol-Gel Sci Technol* 45(1):63–72
- Gidigas MD (1972) Mode of formation and geotechnical characteristics of laterite materials of Ghana in relation to soil forming factors. *Eng Geol* 6(2):79–150
- Hafez MA, Sidek N, Md Noor MJ (2008) Effect of pozzolanic process on the strength of stabilized lime clay. *Electron J Geotech Eng (EJGE)* 13:1–19
- Horpibulsuk S, Rachan R, Raksachon Y (2009) Role of fly ash on strength and microstructure development in blended cement stabilized silty clay. *Soils Found* 49(1):85–98
- JCPDS (1995) Index to the powder diffraction file. International center for diffraction data, Swarthmore, Pa
- Kassim KA, Chow SH (2000) Consolidation characteristics of lime stabilized soil. *Jurnal Kejuruteraan Awam* 12(1):31–42
- Kassim KA, Hamir R, Kok KC (2005) Modification and stabilization of Malaysian cohesive soils with lime. *Geotech Eng* 36(2):123–132
- Katz LE, Rauch AF, Liljestrand HM, Harmon JS, Shaw KS, Albers H (2001) Mechanisms of soil stabilization with liquid ionic stabilizer. *Transp Res Rec: J Transp Res Board* 1757(1):50–57
- Liu J, Shi B, Jiang H, Huang H, Wang G, Kamai T (2011) Research on the stabilization treatment of clay slope topsoil by organic polymer soil stabilizer. *Eng Geol* 117(1):114–120
- Marasteanu MO, Hozalski R, Clyne TR, Velasquez R (2005) Preliminary laboratory investigation of enzyme solutions as a soil stabilizer (No. MN/RC-2005-25)
- Marel HWVD, Beutelspacher H (1976) Atlas of infrared spectroscopy of clay minerals and their admixtures. Elsevier Scientific Publishing, Amsterdam
- Marto A, Latifi N, Sohaei H (2013) Stabilization of laterite soil using GKS soil stabilizer. *Electron J Geotech Eng (EJGE)* 18:521–532
- Mitchell JK, Soga K (2005) Fundamentals of soil behavior, 3rd edn. John Wiley and Sons, New York
- Nacamoto K (1970) Infrared spectra of inorganic and coordinated compounds. Wiley, New York
- Ojuri OO, Ogundipe OO (2012) Modeling used engine oil impact on the compaction and strength characteristics of a lateritic soil. *EJGE* 17:3491–3501
- Ou O, Zhang XG, Yi NP (2011) The experimental study on strength of subgrade soil treated with liquid stabilizer. *Adv Mater Res* 194:985–988
- Phair JW, Van Deventer JSJ (2002) Effect of the silicate activator pH on the microstructural characteristics of waste-based geopolymer. *Int J Miner Process* 66(1):121–143
- Rajasekaran G, NarasimhaRao S (1997) Lime stabilization technique for the improvement of marine clay. *Soils Found* 37(2):97–104
- Rauch AF, Harmon JS, Katz LE, Liljestrand HM (2002) Measured effects of liquid soil stabilizers on engineering properties of clay. *Transp Res Rec: J Transp Res Board* 1787(1):33–41
- Santoni RL, Tingle JS, Webster SL (2002) Stabilization of silty sand with nontraditional additives. *Transp Res Rec: J Transp Res Board* 1787(1):61–70
- Santoni RL, Tingle JS, Nieves M (2005) Accelerated strength improvement of silty sand with nontraditional additives. *Transp Res Rec: J Transp Res Board* 1936(1):34–42
- Scholen DE (1995) Stabilizer mechanisms in nonstandard stabilizers. In: Transportation research board conference proceedings (No. 6)
- Solanki P, Zaman M (2012) Microstructural and mineralogical characterization of clay stabilized using calcium-based stabilizers. In: Scanning electron microscopy. Intech, Rijeka, 771–798
- Sukmak P, Horpibulsuk S, Shen SL, Chindaprasit P, Suksiripattana-pong C (2013a) Factors influencing strength development in clay–fly ash geopolymer. *Constr Build Mater* 47:1125–1136
- Sukmak P, Horpibulsuk S, Shen SL (2013b) Strength development in clay–fly ash geopolymer. *Constr Build Mater* 40:566–574
- Syafalni, Lim HK, Ismail N, Abustan I, Murshed MF, Ahmad A (2012) Treatment of landfill leachate by using lateritic soil as a natural coagulant. *J Environ Manag* 112:353–359
- Tingle JS, Santoni RL (2003) Stabilization of clay soils with nontraditional additives. *Transp Res Rec: J Transp Res Board* 1819(1):72–84
- Tingle JS, Newman JK, Larson SL, Weiss CA, Rushing JF (2007) Stabilization mechanisms of nontraditional additives. *Transp Res Rec: J Transp Res Board* 1989(1):59–67
- Townsend FC (1985) Geotechnical characteristics of residual soils. *J Geotech Eng Div* 111(1):77–94
- Zhang T, Xu YY, Wang H (2012) Application and curing mechanism of soil stabilizer. *Adv Mater Res* 557:809–812
- Zhu ZD, Liu SY (2008) Utilization of a new soil stabilizer for silt subgrade. *Eng Geol* 97(3):192–198