Journal of GeoEngineering, Vol. 16, No. 1, pp. 023-034, March 2021
http://dx.doi.org/10.6310/jog.202103_16(1).3

PERFORMANCE OF SAND DUNES IN STABILIZING HIGHLY EXPANSIVE SOIL

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ABSTRACT

The expansive soil and sand dunes are abundant in desert areas at which new cities have been constructed. One of the effectively mitigation techniques for the expansive soil is to mix it with a non-swelling soil. This paper aims to study the influence of different sand dunes fractions, varying from zero to 50%, on the behaviour of the highly expansive clay. The clay-sand mixtures were also chemically stabilized by 10% of lime. The samples were remoulded according to the modified AASHTO compaction tests results. Swelling and strength tests were performed on each mixture. The results showed that mixing sand dunes with expansive clay reduced its swell potential and swelling pressure. The reductions increased as the increment of sand fraction. The swell potential and swelling pressure of the clay reduced to approximately the one-third when utilizing 50% sand. But mixing lime and sand with clay caused further significant reductions in swell properties. The swell potential and the swelling pressure of the clay were approximately suppressed when it was stabilized by 50% sand and 10% lime. Adding sands to clays had a negative effect on the strength. The CBR and UCS values of the clay-sand mixture decreased with increasing sand fractions. Once adding lime to the clay-sand mixtures, the CBR and UCS after 8-weeks curing time increased. The increments raised with increasing of sand fraction. The existence and the increment of sand dunes in clay influenced effectively on the chemical reactions with lime.

Key words: Expansive clay, sand, swell potential, swelling pressure, strength.

1. INTRODUCTION

Expansive soils are mainly widespread in arid and semi-arid regions which cover large areas. Due to the population growing all over the world, new cities have been constructed on these regions. Constructing infrastructures and buildings on expansive soil is a big challenge for geotechnical engineers. Expansive soils have a good performance under structures if they don't subject to water immersion. In the later condition, the expansive soils are in stiff or very stiff states (Farook and Virk 2009; Elkady 2014). Once the expansive soils are saturated, they heave or induce swelling pressure resulting in partial or full damages to various civil engineering structures, especially to lightly loaded structures like pavements, canal linings, *etc*. This is attributable to the saturation causes swelling pressure and the losing strength of the expansive soil under structures (Williams and Donaldson 1980; Chen 1981; Verma and Marus 2013; Al Fouzan and Dafalla 2014). The clay mineral of montmorillonite is responsible for the generation of the expansive behaviour (Bachouche and Boutaleb 2013; Aref *et al.* 2014).

The expansive soils, particularly highly swelling clay, should be treated effectively to prevent the damages of structures on them. The existence of expansive soils is mainly in desert regions at which the sand dunes are abundant. One of the improvement techniques of expansive soil is to mix it with a non-swelling soil like sand dunes. Using sand dunes as a mechanical stabilization of expansive soil is instead of the expansive soil replacement. The expansive soil is usually replaced by an expensive structural fill due to its price and transportation costs from the resource which may be far from construction sites. Sand dunes have usually a similar grain sizes and approximately rounded shapes as well as they are poorly graded non-plastic fine to medium sand. The sand dunes also possess a high porosity and a low bearing capacity. Moreover, sand dunes may induce a collapsible behaviour due to solving cement materials under water immersion (Kettab *et al.* 2003; Fattah *et al.* 2016; Tiwari *et al.* 2016; Mustapha *et al.* 2019). The function of the mechanical soil stabilization is to alter the physical composition of a soil by mixing it with another soil. The mechanical stabilization is achieved by compacting the mixed soils. The soil improvement using mechanical stabilization depends mainly on the particle size distribution, mixing quality and the compaction degree of the blended soils. Moreover, the stabilized expansive clay with sand leads to decrease the mixture void ratio because the clay particles are distributed uniformly and they enter in the mixture voids. The volume change of the expansive clay reduces effectively due to the increment of the bonds between the sand and the clay particles as well as the decrement of the bonds between the clay particles (Louafi and Bahar 2012). Few studies investigated the stabilized expansive clay mechanically by sand. Blending expansive clay with different sand fractions causes reductions in the optimum moisture contents, swell potential, swelling pressure and compression index, as well as it causes increment in the maximum dry density (Phanikumar *et al.* 2010; Louafi and Bahar 2012; Rama *et al.* 2014; Daipuria and Trivedi 2016; Kollaros and Athanasopoulou 2016; Rathod and Sathe 2017; Qin-Yong *et al.* 2018; Amri *et al.* 2019). Moreover, the unconfined compressive strength

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Manuscript received August 18, 2020; revised February 1, 2021; accepted February 18, 2021.

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of clay-sand mixtures decreases at higher sand fractions (Jjuuko *et al.* 2011; Kollaros and Athanasopoulou 2016; Qin-Yong *et al.* 2018; Amri *et al.* 2019). Amri *et al.* (2019) studied the improvement of stabilized highly plastic clay with sand dunes such as its plasticity index and strength.

The expansive soil is a problematic soil and the sand dunes have poor geotechnical properties. Stabilizing expansive soil aims to solve completely the swelling problem. Stabilization of expansive clay with sand dunes may sustain from somewhat high values of swelling. Hence, the expansive soil-sand dunes mixtures need additional improvement by a chemical stabilization to gain more reduction in the swelling and more increment in the strength. The chemical stabilization can be cement, fly ash, silica fume or lime. The lime stabilization is the most effective in improving the engineering properties of the expansive soil in the mixture. The reasons of that are the lime is a cheap material and the paucity of the structural fill (Reddy *et al.* 2015). The effective enhancement is attributable to the chemical reactions between clay minerals and lime in the presence of water depending on curing time. The chemical reactions include the short-term (modification/flocculation) and long-term (stabilization/solidification). Once the lime is added to clayey soil, the short-term reaction starts between the ions in the surface of clay particles and the calcium ions in the lime (cation exchange). The short-term reaction induces clay particles flocculation and the soil looks like granular soil improving soil workability, swelling properties, compressibility, particle size and permeability (Clare and Cruchley 1957; Diamond and Kinter 1965; Eades and Grim 1966; Basma and Tuncer 1991; McKallister and Petry 1992; Bell 1996; Afès and Didier 2000; Nalbantoglu and Tuncer 2001; Khattab 2002; Al-Rawas *et al.* 2005; Alper *et al.* 2006). After several hours at the end of the short-term reaction, the long-term reaction starts between the silica and some alumina in the clay minerals, and calcium ion in a highly alkaline environment (the pH value of pore fluid reaches 12.4). This chemical process forms new cementitious components: calcium aluminate hydrates (CAH), calcium silicate hydrates (CSH), and calcium alumino-silicate hydrates (CASH) (Eades and Grim 1960; Clara and Handy 1963; Ormsby and Kinter 1973; Cabrera and Nwakenma 1979; Arabi and Wild 1986; Wild *et al.* 1986; Locat *et al.* 1990; 1996; Bell 1996; Rajasekaran and Rao 1997; Khattab 2002; Al-Mukhtar *et al.* 2010; 2012; Schanz and Elsawy 2015; 2017; Yunus *et. al.* 2017; Aldaood *et. al.* 2018; Ismaiel and Abdellateef 2018). The long-term reactions produce flocculation and cementing soil particles together in the microstructure resulting in improving the strength and the bearing capacity. This reaction, called pozzolanic reaction, increases the improvement with the increment of curing-time and temperature (Arabi and Wild 1986; Bell 1996; Boardman *et al.* 2001; Sudhakar and Shivananda 2005; Schanz and Elsawy 2017; Ismaiel and Abdellateef 2018). The effective improvement occurs when the percentage of lime in the mixture is suited and enough to the clay minerals (Hill and Davidson 1960). Several past research investigated the stabilization of expansive soil with lime and they found that reductions occur in swelling properties, volume change, plasticity index, and maximum dry density as well as increments develop in particle size, permeability, optimum moisture content and strength values (Al-Mukhtar *et al.* 2010; 2012; Louafi *et al.* 2015; Schanz and Elsawy 2015; Elkady 2016; Souad *et al.* 2017; Yunus *et. al.* 2017; Aldaood *et. al.* 2018; Ismaiel and Abdellateef 2018; Worku *et al.* 2019). While very few past researchers studied the stabilization of expansive clay with sand dunes only (Amri *et al.* 2019) or sand incorporation with lime (Mir *et al.* 2018). Consequently, past researchers didn't study the effect of sand dunes on the characteristics of the highly expansive soil.

Therefore, the objective of the current research is to study the mechanical stabilization of the highly expansive clay by mixing it with sand dunes. Particularly, the sand dunes are available and abundant near the expansive soil in the arid and semi-arid regions. The sandy soil is utilized as fractions by weight in the highly expansive clay. In order to achieve more enhancements in the highly swelling soil-sand dunes mixtures, the hydrated lime is utilized. The lime is used because of the sand dunes, having poor geotechnical properties, need also to be improved. Hence, the stabilization of the highly expansive clay using sand dunes only and sand dunes-lime mixtures needs to be outlined. Additionally, the influence of sand dunes with or without lime on the swelling parameters of the highly expansive soil is not only important but also the strength and the bearing capacity of the improved expansive soil is necessary to be studied.

In the current research, the experimental tests of the modified AASHTO compaction, swell potential, swelling pressure, California bearing ratio, CBR and unconfined compression strength, USC have been performed on the samples of the non-treated highly expansive clay, and the stabilized highly expansive clay with sand only and with sand-lime mixtures. The stabilized clay with sand possesses sand contents of 20%, 30%, 40%, and 50% by weight. Additionally, the clay-sand mixtures are stabilized using 10% hydrated lime by weight. The comparison between the effects of the mechanical stabilization and the mechanical-chemical stabilization on the behaviour of the highly expansive clay has also been investigated.

2. MATERIALS AND METHODS

2.1 Materials

Ca-bentonite from Bavaria Südchemie Company in Germany with high plasticity, called Calcigel bentonite, is utilized as a highly expansive clay. The characteristics of Ca-bentonite are illustrated in Table 1 (Arifin 2008). The highly expansive clay is mechanically stabilized by sand dunes. The sand (fine to medium sand) is a poorly graded sand (SP) according to the unified soil classification system (USCS). The sand is mainly consisted of Silicon Dioxide. The properties of sand are illustrated in Table 2. The used lime is the hydrated lime (calcium hydroxide Ca(OH)) which has been produced at Colony Factory in Germany.

Table 1 Properties of the used Bentonite

Properties	Value
Specific Gravity	2.8
Liquid limit (%)	180
Plastic limit (%)	56
Plasticity index (%)	124
Shrinkage limit (%)	18
Clay content (%)	40
Fine content (%)	100
External specific surface area (m^2/g)	81
Total specific surface area (m^2/g)	525
Montmorillonite content (%)	50 ~ 60

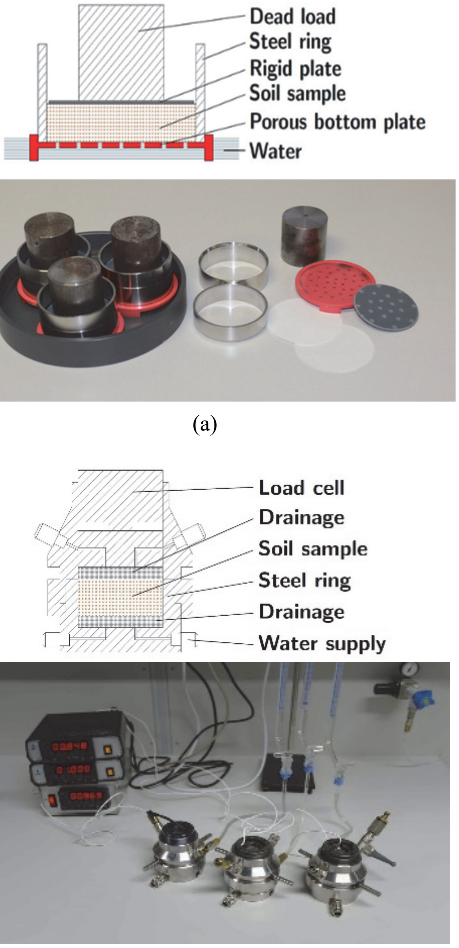
Table 2 Properties of the used sand

Properties	Value
SiO_2 (% by weight)	99
Al_2O_3 (% by weight)	0.3
Fe_2O_3 (% by weight)	0.05
TiO_2 (% by weight)	0.08
Specific Gravity	2.65
e_{max}	0.901
e_{min}	0.556
d_{10} (mm)	0.14
D_{30} (mm)	0.2
D_{60} (mm)	0.25
Cu	1.79
Cc	1.14
Classification (USCS)	SP

2.2 Methods

The modified compaction AASHTOO (T-180) tests were performed on Ca-bentonite blended with sand contents of 0%, 20%, 30%, 40%, and 50%, without and with 10% hydrated lime fractions to evaluate the effect of mechanical and chemical stabilization on the compaction properties of the treated soil. In the samples preparation stage, the dry materials containing bentonite and sand as well as bentonite, sand and hydrated lime were homogenously blended. After that, distilled water was added. Each sample contents were also homogenously mixed with the water. The non-stabilized and the stabilized clay samples were saved in closed plastic bags for at least one-week before testing. The one-week time was utilized to guarantee spreading water in the entire sample and as a curing period for the chemical reactions in the lime-sand-bentonite mixtures (Schanz and Elsawy 2017). Each sample was prepared according to the maximum dry density and the optimum water content obtained from the results of the modified AASHTO compaction tests before performing swelling and strength tests. Further unconfined compressive strength tests were carried out on clay-sand samples stabilized with hydrated lime fraction of 10% after curing periods of 14, 21, 28, and 56 days to examine the influence of curing time on the stabilized clay strength.

Swell potential is known as a percentage of heave displacement respect to the original height of the specimen. While the swelling pressure is defined as the required pressure to inhabit swelling. The swell potential test was conducted on each compacted sample using oedometer apparatus. The oedometer ring has 7 cm diameter and 2 cm height as shown in Fig. 1(a). In order to platen the sample properly during the test, it was loaded by a seating load of 6.0 kPa. Then the sample was immersed with distilled water and it was permitted to swell. Heave displacements were recorded at 0, 1, 2, 4, 8, 15, 30, 60, 120, 240, 480, and 1440 min, and then every 4 hours on subsequent days until no further heave was noticed (Schanz and Elsawy 2017). The ratio between the heave increment and the original height of a sample, expressed as a percentage, is utilized as percent swell in this paper. In the other side, an isochoric (volume constant) cell with sample size of 5 cm diameter and 2 cm height was utilized to determine the swelling pressure as depicted in Fig. 1(b). Swelling pressure was registered by an internal load cell. A digital device connecting to it reads the swelling pressure along time. Each test was finished when the reading became constant (Schanz and Elsawy 2017).



(a)

(b)

Fig. 1 (a) Swelling rin; (b) Isochoric cell

3. TESTS RESULTS AND DISCUSSIONS

The results of the modified AASHTO compaction tests on the non-treated expansive clay, expansive clay-sand, and expansive clay-sand-lime samples are presented in Figs. 2 and 3. Once the clay is mixed with sand contents of 20%, a significant increment in the maximum dry density (MDD) and a sharp decrement in the optimum moisture content (OMC) occur. The maximum dry density increases from 13.4 kN/m^3 to 15.5 kN/m^3 while the optimum moisture content decreases from 35% to 28% when using only 20% sand in clay. The increment of sand proportions leads to further increasing in the maximum dry density and additional reductions in the optimum moisture content. The sand percentage of 50% in clay causes an increment in the maximum dry density from 13.4 kN/m^3 to 16.5 kN/m^3. Consequently, the optimum moisture content reduces from 35% to 23%. The rate of maximum dry density increasing, and optimum moisture content decreasing is small between 20% and 30% sand contents. Both rates increase beyond the sand fraction of 30% as depicted in Figs. 3(a) and 3(b). The clay-sand mixtures with sand fractions of 30%, 40%, and 50% are chemically stabilized by 10% hydrated lime. Adding lime to the clay-sand mixtures leads to an important reduction in the maximum dry density as well as an increment in the optimum moisture content and the porosity for all the mixtures. While the existence and the increment of sand dunes in the clay-lime mixtures cause the opposite of those of lime as illustrated in Figs. 2 and 3.

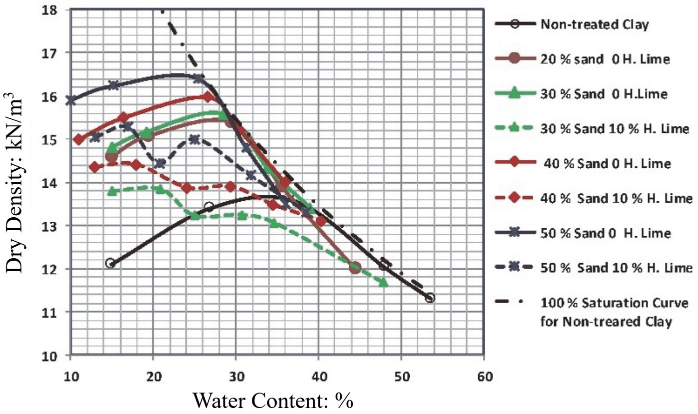
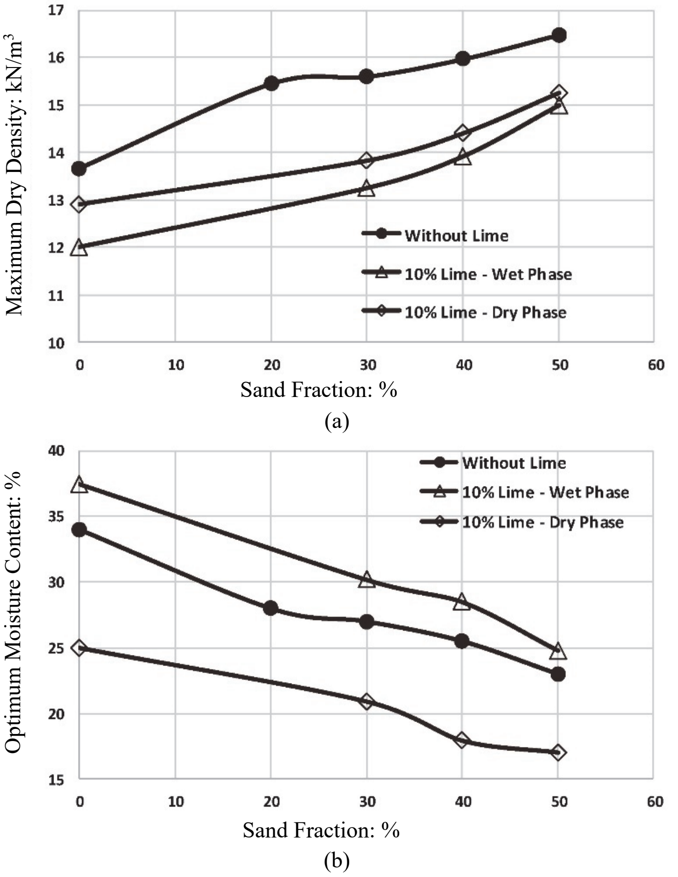


Fig. 2 Compaction curves for untreated and treated clays with sand and sand-lime mixtures



(a)

(b)

Fig. 3 (a) Variation of optimum moisture content with sand percentages; (b) Variation of maximum dry density with sand percentages

Hence, stabilizing clay-sand mixtures by lime has an effective economical side by reducing the quantity of the compacted expansive soil-sand mixture and compaction energy costs. The reason for that is the resulted improvements from the short-term reaction between lime and clay minerals in the clay-sand mixtures such as the flocculation and aggregation. The flocculation and the aggregation cause an effective improvement in the workability of the clay–sand–lime mixtures. Therefore, stabilizing clay with lime-sand mixtures converts the natural clay to soil similar to coarse-grained soils. As known, coarse-grained soils need smaller compaction effort than soils containing excess clay.

Additionally, adding 10% lime to clay-sand mixtures generates double peak values of dry density as shown in Figs. 2 and 3. The double peak values of dry density are more pronounced in the clay-sand-lime mixture having 50% sand percentage. The first peak is known as dry peak compaction point, DPCP, because it has a lower water content. While the second peak is located at the greater water content and is named as wet peak compaction point, WPCP (the original OMC). Schanz and Elsawy (2017) stated that many experimental studies induced compaction curves with double peaks (Hindi 1967; Lee and Suedkamp 1972; Ellis 1980; Razouki *et al.* 1980; Dixon 1985; Benson *et al.* 1997; Sun *et al.* 2007; Razouki *et al.* 2008; Albadran 2011). Belchior *et. al.* (2017a, 2017b) stated that swelling clay samples compacted with WPCP required only 2% of lime to prevent the swelling, whereas the samples compacted at DPCP needed 4% of lime to avoid expansion. Additionally, in the current research, it is observed that the hydrated lime-bentonite-sand mixtures at WPCP have greater workability than those at DPCP. Therefore, the hydrated lime-bentonite-sand samples for the swelling and strength tests were compacted according to WPCP.

3.1 Effect of Stabilization on Swell Characteristics

3.1.1 Swell Potential

Figure 4 shows the development of swell potential along time for soil samples mixed with varying amount sand fractions (0% ~ 50%) without and with hydrated lime of 10%. The swell percent increases with developing time for all samples. The non-treated clay sample implies the maximum swell potential of 34.5%. When mixed the highly expansive clay with 30% of sand, the swell potential decreases. The reduction in swell percent continues with increasing sand fractions. Using 50% sand in clay reduces the swell percent from 34.5% to 11%. This is attributable to the sand is a non-swelling soil. The increase of sand leads to the decrement of swelling clay contents in the whole mixtures.

Utilizing 10% hydrated lime beside sand in the highly expansive soil causes an additional decrement in the swell percent and swell time. The swelling of the stabilized highly expansive soil by sand-lime mixtures was finished within 3 days resulting in swelling time shorter than that of the non-treated soil and stabilized soil with sand. The swell percent and swell time of the clay-sand-lime mixtures decrease effectively with the increment of sand contents. The swell percent of the clay-sand-lime mixtures decrease from 34.5% to 1.5% and 1% when using 30% and 40% sand fractions. Consequently, stabilizing highly expansive clay with 10%-lime and 50%-sand eradicates permanently the swell potential as illustrated in Fig. 4.

The variation of the normalized swell potential of clay-sand mixtures without and with 10% lime for various sand fractions is drawn in Fig. 5(a). The swell potential values are normalized to the swell potential of the non-treated clay. This figure emphasizes that as the sand fractions increase, the swell potential decreases gradually. The reduction rate of swell potential between 40% and 50% sand is the smaller when compared with the lower percentages of sand. When the clay-sand mixtures are mixed with 10% lime, a significant reduction occurs in the swell potential. Moreover, utilizing 10% lime as a chemical stabilization for clay-sand mixtures leads to minimizing the swell potential. The swell potential reduction increases with increasing sand fractions till reaching a zero value of swell potential at 50% sand and 10% lime. The swell

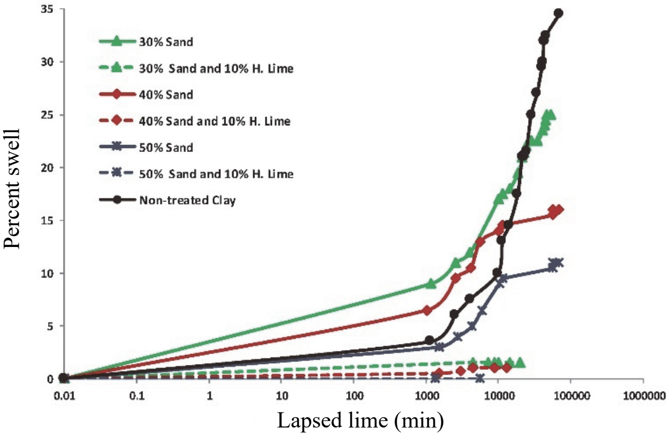
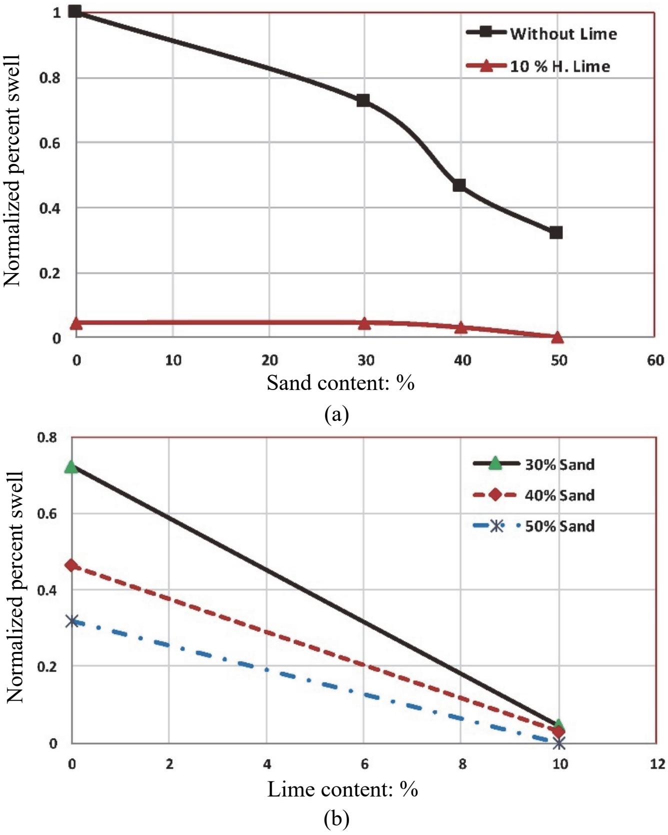


Fig. 4 **Time histories of Percent Swell for the non-treated and treated clay with sand and lime**

potential reduction rate of clay-sand mixtures without lime is greater than those stabilized by lime. Otherwise, when using 10% lime, the reduction rate of the swell potential is the greater when using sand fractions more than 30%.

Figure 5(b) illustrates the variation of the normalized swell potential with developing lime content for different sand fractions. This figure confirmed that adding sand to highly expansive clay decreases the swell potential. Additionally, the clay-sand mixtures stabilized with 10% lime imply so lower values of swell potential when compared to the stabilized clay with sand only. The swell potential of clay-lime mixtures decreases also with the increment of sand fractions. The smaller the reduction rate of the swell potential is, the greater the sand contents are.



(a)

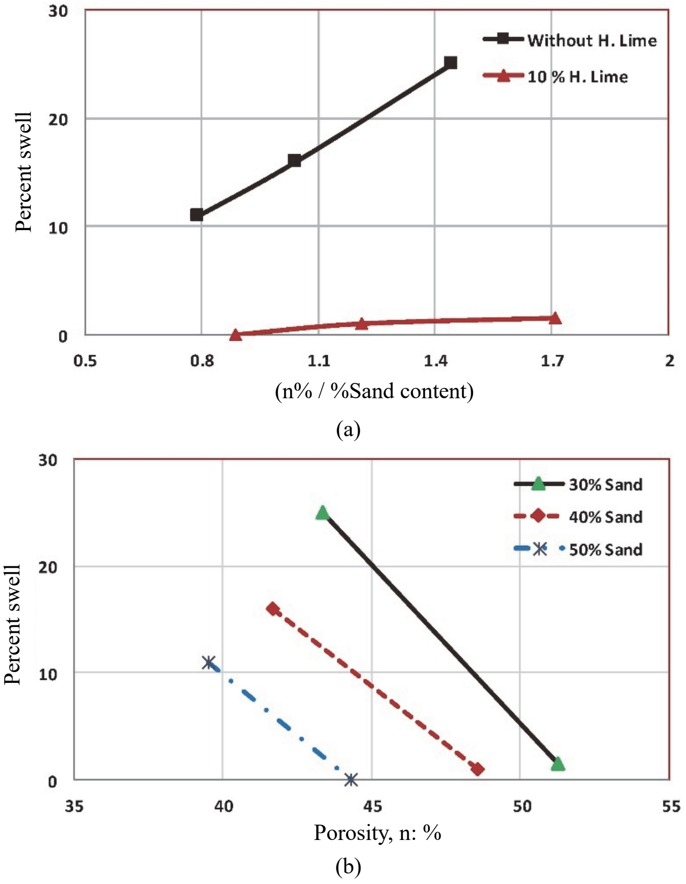
(b)

Fig. 5 **(a) Reductions of Percent Swell with developing sand content; (b) Reductions of Percent Swell with developing lime content for different sand fractions**

Figure 6(a) indicates the variation of swell potential with the ratio between the porosity and %sand in the clay-sand mixtures without and with lime. The increment of sand fraction in clayey soil causes reductions in the porosity. The swell percent of the clay-sand mixtures decreases with a constant rate with decreasing the porosity and %sand ratio. Consequently, the swell percent of the clay-sand-lime mixtures induces also a decrement but with a variable rate as reducing the porosity and %sand ratio. Adding lime to each clay-sand mixture causes an increment in the porosity resulting in significant decrements of the swell potential as illustrated in Fig. 6(b). The porosity increment is an indication for improvement in the workability and permeability of the whole mixture. The later results agree well with the findings of Silvani *et al.* (2020).

3.1.2 Swelling Pressure

Figure 7 illustrates the relationship between the swelling pressure and the swelling time for the non-treated and the treated expansive soil using different contents of sand without and with 10% lime. The incremental trend of swelling pressure with time is approximately similar for all samples. The swell pressure value of the non-treated clay sample is high which equals 880.6 kPa which classified as a highly expansive soil. As the sand is mixed with the expansive clay, the swelling pressure reduces. The swelling pressure



(a)

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Fig. 6 **(a) Developing Percent Swell along the ratio of porosity to sand percentage; (b) Developing Percent Swell along the values of porosity for different sand fractions with and without lime**

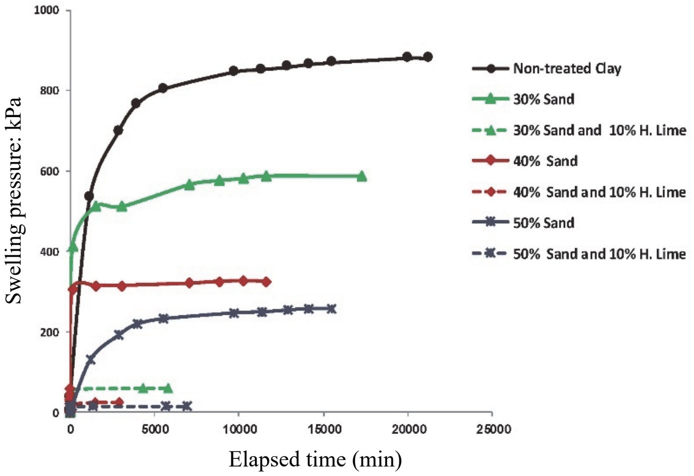
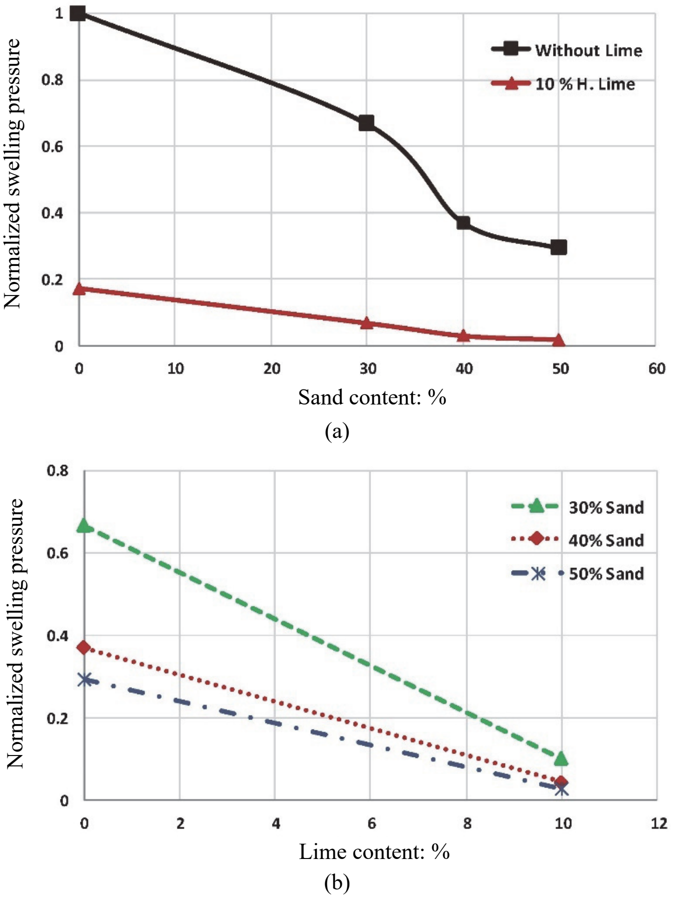


Fig. 7 Time histories of swelling pressure for the non-treated and treated clay

has further reductions with the increment of sand contents from 30% to 50% in the expansive clay. The swelling pressure reduces to a value of 66.6%, 37.0%, and 29.3% of that of the non-treated clay when the clay is mechanically stabilized by 30%, 40%, and 50% of sand, respectively. Consequently, the stabilization of the clay by sand fractions greater than 30% is the more effective in reducing swelling pressure. These reductions are attributable to utilizing sand, as a non-swelling soil, which leads to a decrease in the swelling characteristics of the highly expansive clay. When the clay-sand mixtures are chemically stabilized by 10% lime, the swelling pressure and time are minimized. The swelling pressure of the clay-sand-lime mixtures decreases strongly with increasing sand fractions. The stabilization of the clay-lime mixtures by sand fractions greater than 30% cause the more significant reduction of the swelling pressure.

In Figs. 8(a) and 8(b) the swelling pressure values of the treated soil are normalized to the swelling pressure of the non-treated soil. Figure 8(a) also indicates the variation of the normalized swelling pressure with developing sand content for 0% and 10% lime fractions. This figure emphasized that adding sand to clay decreases gradually the swelling pressure. Moreover, utilizing 10% hydrated lime fraction as a chemical stabilization, the swelling pressure of the clay-sand mixtures decreases significantly. The swelling pressure of clay-sand-lime mixtures decrease to 10.1%, 7.8%, and 5.9% of that for the clay-sand mixtures including 30%, 40%, and 50% sand contents, respectively. The reduction rate of the swelling pressure of the stabilized clay-sand mixtures without lime is greater than that of the stabilized clay-sand mixtures with 10% lime. The reduction rate of swelling pressure is the greater of the stage between 30% and 40% for both 0% and 10% lime compared by the other stages of sand percentages (between 0% and 30%, and between 40% and 50%).

Figure 8(b) also shows the variation of the normalized swelling pressure with and without lime for sand fractions of 30%, 40%, and 50%. This figure also compared between the reduction of swelling pressure of the clay-sand and the clay-sand-lime mixtures. Therefore, using lime content 10% in the expansive clay-sand mixtures with sand fractions greater than 30% leads to minimize the swelling pressure. The greater the reduction rate of the swelling pressure in the clay-sand-lime mixtures is, the smaller the sand fraction is.



(a)

(b)

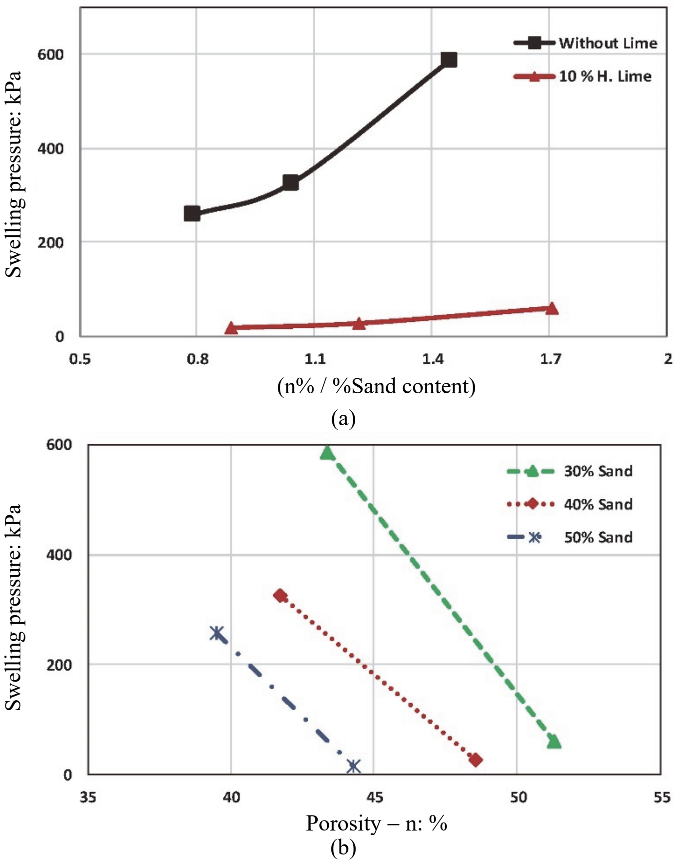
Fig. 8 (a) Swelling pressure reduction with developing sand contents for the treated clay; (b) Swelling pressure reduction with developing lime content for the treated clay

The swelling pressure increases as the increment of the ratio between the porosity and the sand percent as indicated in Fig. 9(a). Stabilizing highly expansive soil with sand dunes reduces the porosity and the swelling pressure as well as increasing the maximum dry density. While utilizing 10% lime in each clay-sand mixture causes a sharp reduction in the swelling pressure values generating increments in the porosity values and decrements in the maximum dry density (Fig. 9(b)). This trend is associated with increasing porosity and interparticle space during the short-term chemical reactions between bentonite-sand mixtures and lime in the existence of water. At which the calcium ion tends to replace weak metallic cations on the surface of clay particles. Increasing the porosity permits the available volume for the particles to rearrangements sharply mitigating internal swelling pressure and degree of volume increase. A 10% hydrated lime is suitable and enough for short-term reaction of the highly expansive clay-sand mixtures. Moreover, the stabilized highly expansive clay using 50% sand and 10% lime enhanced effectively the swelling characteristics of the clay resulting in removing swell potential and minimizing swelling pressure of the highly expansive clay.

3.2 Effect of Stabilization on Strength Characteristics

3.2.1 California Bearing Ratio (CBR)

California Bearing Ratio (CBR) tests were also conducted on the non-treated clay, the clay-sand and the clay-sand-lime samples stabilized by sand contents varying from 0% to 50% without and



(a)

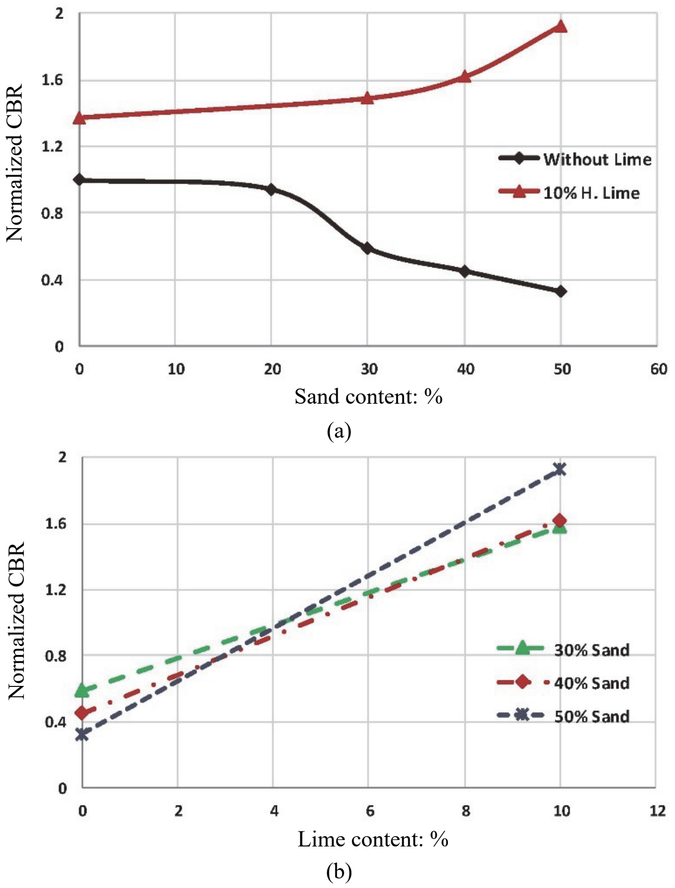
(b)

Fig. 9 **(a) Developing swelling pressure along the ratio of porosity to sand percentage; (b) Developing swelling pressure along the values of porosity for different sand fractions with and without lime**

with lime content of 10% as illustrated in Figs. 10(a) and 10(b). The CBR tests were performed after 7 days curing time. CBR values are also normalized to the CBR value of the non-stabilized clay. The non-stabilized clay induces a high value of CBR which reaches 35.8%. When the clay is mixed with 20% sand soils, CBR values decrease. The CBR reduction continues significantly with increasing sand contents in the clay. The CBR of the clay decreases from 35.8% to 33.8%, 21%, 16.1%, and 11.7% when the clay is mixed by sand fractions of 20%, 30%, 40%, and 50%, respectively. Hence, the sand has a negative effect on the CBR values of the clay-sand mixtures. The reduction rate of the CBR is greater in the stage between sand contents of 20% and 30% when compared with the other sand contents stages.

Once the clay-sand mixtures are chemically stabilized by 10% lime, the reduction in CBR values converts to increment in them. There are further significant increments in CBR with increasing sand fractions. The CBR of clay-sand-lime mixtures increases to 2.5, 3.6, and 5.9 times of that for the clay-sand mixtures containing 30%, 40%, and 50% sand contents, respectively. The CBR increment rate of the clay-sand-lime mixtures is the greater in the final stage between 40% and 50% sand fraction compared to the other stages with lower sand contents.

Figure 10(b) also shows the normalized CBR of the stabilized clay with 30%, 40%, and 50% sand without and with 10% lime. The clay-sand-lime mixtures imply CBR values greater than those of the clay-sand mixtures. The increment rate of CBR increases with the increment of sand fractions. The greater and the smaller CBR increment rate occurs at 50% and 30% sand contents, respectively. The maximum CBR value occurs when stabilized clay with 50% sand and 10% lime. More enhancements in the CBR values of the clay-sand-lime mixtures are expected with longer curing times.



(a)

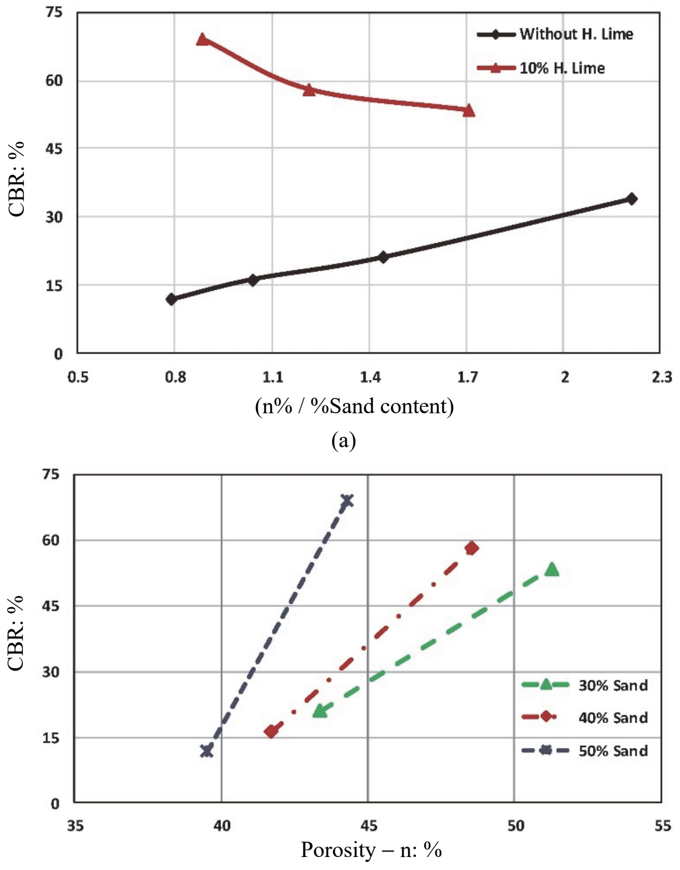
(b)

Fig. 10 **(a) CBR for the treated clay with developing sand contents; (b) CBR with developing lime content for various sand fractions**

The CBR values increase linearly with the increment of the ratio between the porosity and the sand percentage as depicted in Fig. 11(a). The smaller the sand contents in the clay is, the greater the CBR and porosity values are. While the opposite occurs when adding 10% lime to the clay sand mixtures, the CBR values reduce non-linearly as increasing porosity-%sand ratio. Stabilizing each sand-clay mixture with 10% lime increases linearly the porosity resulting in an important increment in the CBR values as illustrated in Fig. 11(b). The increment of porosity in the clay-sand-lime mixtures expresses the increase of voids between the flocculated and the aggregated particles which formed in the short-term chemical reaction. The voids strongly support to continue the long-term chemical reaction between the clay minerals and the hydrated lime permitting more particles rearrangements. The long-term chemical reaction leads to increase the bearing ability of the stabilized clay.

3.2.2 Unconfined Compressive Strength (USC)

The stress-strain relationships of the unconfined compression strength tests are depicted in Fig. 12 for the non-treated clay, clay-sand and clay-sand-lime samples with sand fractions ranging from 0% to 50% and lime content of 10%. The development of the stress with the axial strain is approximately similar for the samples of the



(a)

(b)

Fig. 11 (a) CBR values for the treated with developing the ratio of porosity to sand percentage; (b) CBR values with developing Porosity for various sand fractions with and without lime

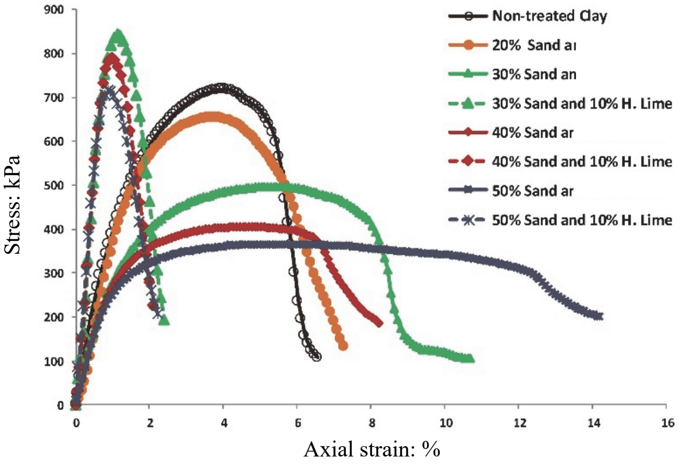
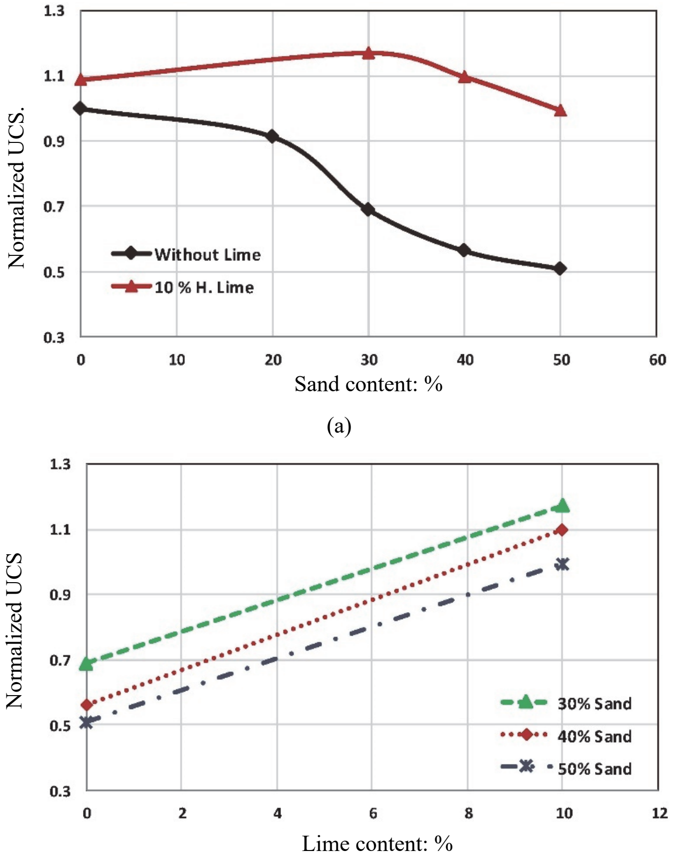


Fig. 12 **Stress and axial strain relationships for the non-treated and treated clay with sand and sand-lime mixtures**

non-treated clay and sand treated clay while the clay-sand-lime mixtures have a different trend. All samples possess hardening and softening. The ultimate stress of the non-treated clay occurs at axial strain of 4%. When the clay is stabilized with sand, the ultimate stress occurs at greater values of axial stress except the case of 20% sand. The non-treated clay and clay-sand samples induce ductile behaviour. The ductility behaviour increases with the increment of sand fraction which is more pronounced at using 50% sand content. The peak stress values of the clay-sand-lime samples take place at axial strain values ranging from 0.8% to 1.1%. This confirms that the clay-sand-lime mixtures are stiffer and imply more brittle behaviour when compared to the non-treated clay and the clay-sand samples. The non-treated clay, as it possesses a high value of CBR, exhibits also a high value of unconfined compression strength UCS. The UCS of the non-treated clay equals 719 kPa. Therefore, the results of UCS tests agree well with the results of the CBR tests.

When the clay is mixed with 20% sand only, the UCS decreases. The UCS further deceases significantly with increasing sand content as illustrated in Figs. 12 and 13(a). The USC of clay-sand mixtures decreases to 91.4%, 69%, 56.4%, and 50.9% from that of the non-treated clay as utilizing 20%, 30%, 40%, and 50% sand contents, respectively. This is attributed to the non-treated clay having a high value of UCS. Moreover, The UCS value estimates the cohesion of the soil. The UCS increases with the increment of the soil cohesion. By adding sand to the mixture, as the sand is a non-cohesive soil, the UCS decreases. The USC reduction rate is the greater at the stage between 20% and 30% among the other stages, as illustrated in Fig. 13(a). Beyond the 30% sand content, the USC reduction rate decreases with increasing sand contents.



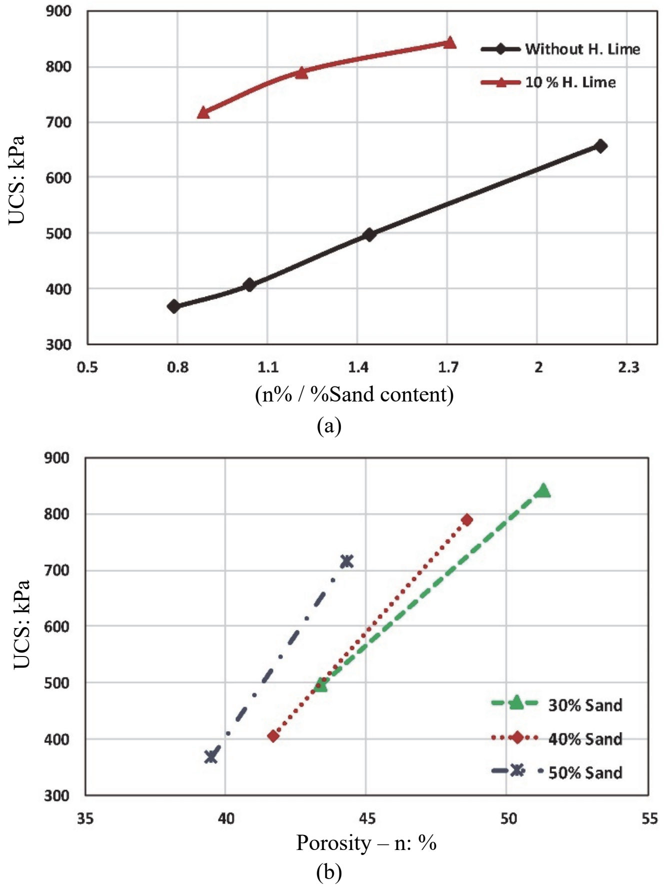
(a)

(b)

Fig. 13 (a) USC for treated clay developing sand contents; (b) USC with developing lime content for various sand fractions

Once the clay-sand mixtures are stabilized with 10% lime proportion, the UCS values increases. The clay-sand-lime mixtures have greater USC values than those of the clay-sand mixtures. The USC of clay-sand-lime mixtures increases to 1.7, 1.95, and 1.96 times of that for the clay-sand mixtures containing 30%, 40%, and 50% sand contents, respectively. The USC of the clay-sand-lime mixtures increases with developing sand contents to 30%. Greater sand contents than 30% lead to reductions in the USC of the clay-sand-lime mixtures. The USC of the clay-sand-lime mixtures increase to 1.17 and 1.1 times of that of the non-treated clay when using 30% and 40% sand contents, respectively. While utilizing 50% sand and 10% lime contents in clay results in approximately the same USC value of the non-treated clay. Figure 13(b) shows the USC values of the clay-sand mixtures without and with 10% lime for 30%, 40%, and 50% sand fraction. The USC increment rate is approximately equal for all studied sand fractions. Using 30% sand fraction in clay without and with lime possesses the greater USC values. The USC values of the clay-sand and clay-sand lime mixtures reduce with the increment of sand fractions.

The USC values imply increments as increasing the ratio between porosity and sand percentage for the treated soil as depicted in Fig. 14(a). Consequently, the treated soil with sand induces lower values of USC than those of the treated soil with sand-lime mixtures. The greater the USC and porosity values are, the smaller the sand proportion is in the treated soil with and without lime. Utilizing lime in each clay-sand dunes mixture leads to an increase the porosity and USC values as shown in Fig. 14(b).



(a)

(b)

Fig. 14 (a) USC values for the treated soil with developing the ratio of porosity to sand percentage; (b) USC values with developing Porosity for various sand fractions with and without lime

The stabilized expansive clay-sand mixtures using hydrated lime content of 10% induced a good improvement in the strength and the bearing ability. This is attributable to the long-term chemical reaction between calcium ions, which is abundant in the lime, and the clay minerals existing in the clay-sand mixtures. The chemical reaction is time dependent. In order to study the influence of curing time on the strength of the clay-sand-lime mixtures, additional unconfined compression strength tests were conducted for longer curing times (14, 21, and 56 days).

Generally, the longer curing time causes enhancements in the USC of the expansive clay-sand-hydrated lime mixtures as depicted in Fig. 15. 7-days curing time induces enhancement in the UCS values of all clay-sand-lime mixtures which are greater than those of non-treated soil and the treated soil with different sand mixtures. But sand proportions greater than 30% implies lower values of USC. 14-days curing time gives the same trend of USC after 7-days but with higher values. The trend of USC values changes after 21-days from decrement to increment for all sand contents having greater USC values than the former curing time. The increments in USC continue after 8 weeks presenting greatest value at 50% sand proportion. Moreover, utilizing curing time 8 weeks results in important increases in UCS values of the clay-sand-lime mixtures to 197.2%, 247.5%, and 386.8% of that for the clay-sand mixtures containing 30%, 40%, and 50% sand contents, respectively. Hence, stabilizing the clay-sand dunes mixture by lime is not only minimize its volume change but also significantly improves its cohesion and strength.

Adding hydrated lime proportion of 10% to clay-sand mixtures induces strength values greater than that for using sand only stabilized clay. The strength of clay-sand-lime mixtures has significant enhancements with longer curing time. The strength enhancements are a result of long-term chemical reaction (pozzolanic reaction). Moreover, the pozzolanic reaction produces cementitious gels which adhere the particles together causing increase in the cohesion strength parameter and the bearing capacity of the stabilized soil. The existence of sand, as a cohesionless soil, in the expansive clay makes the pozzolanic reaction more effective than using only lime in clay along time. This is because the lime contents become more suitable and sufficient for the clay minerals in the whole mixture of the clay-sand dunes. The later reason is an important advantage of utilizing sand dunes as mechanical stabilization for the highly expansive clay together with lime to vanish its swelling and to improve its strength and durability with time as depicted in Table 3.

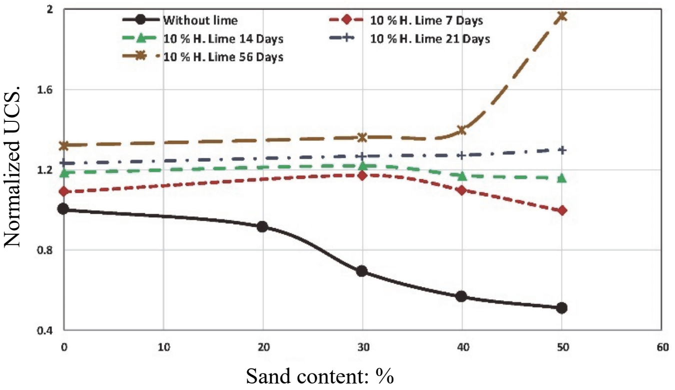


Fig. 15 UCS for various curing period for clay–sand-lime mixtures with developing sand contents

Table 3 Results of the experimental tests after 7 days curing time

Sand fraction, (%)	Lime content (%)	Water content, (%)	Dry density, (kN/m^3)	Percent swell, (%)	Swelling pressure, (kN/m^2)	CBR, (%)	UCS, (kN/m^2)
0	0	34	13.67	34.5	880.57	35.8	719.27
30	0	27	15.6	25	587.22	21	496.25
40	0	25.5	15.97	16	326.46	16.13	405.8
50	0	23	16.48	11	258.21	11.7	366.11
30	10	30.2	13.25	1.5	59.6	53.4	843.1
40	10	28.5	13.92	1	25.46	58	789.77
50	10	24.8	15	0	15.3	69	716.13

4. SUMMARY AND CONCLUSIONS

Swelling and strength tests were performed on the non-stabilized and on the stabilized highly expansive clay mechanically with different sandy soil fractions. As the sand dunes have also poor geotechnical properties, the tests were also conducted on clay-sand mixtures chemically stabilized by 10% hydrated lime to gain more enhancements. This study was achieved to investigate both stabilizations influence on the behaviour of the treated clay. Based on the obtained experimental tests results, the following conclusions can be summarized as follows:

1. The existence of sand dunes in stabilizing highly expansive clay with and without lime leads to increments in the maximum dry density and decrements in the OMC and the porosity values. There are further maximum dry density increments, and OMC and porosity decrements with increasing sand fractions. Stabilizing each clay-sand mixture with 10% lime causes the converse. The maximum dry density decreases significantly, and the OMC and the porosity increase when utilizing 10% lime in each clay-sand mixture. On the other hand, double peak values of dry density in the dry phase and the wet phase are produced in the compaction curves of the clay-sand-lime mixtures.
2. Utilizing sand dunes in the expansive soil causes reduction of its porosity, swell potential, swelling pressure and swelling time. There are further reductions in the swell properties and porosity with increasing sand contents. The porosity induces reducing effect with the swelling properties decrements of the clay-sand mixtures. While adding 10% lime to each clay-sand mixture leads to a significant reduction in its swell potential, swelling pressure and swelling time as well as an increment in its porosity. The swell potential and the swelling pressure decrease effectively with increasing sand contents in the clay-sand-lime mixtures. The swell potential and swelling pressure are almost vanished when the highly expansive clay is mechanically and chemically stabilized by 50% sand dunes and 10% lime, respectively. The existence and the increase of sand dunes in the clay enhances effectively the chemical reaction generated by lime.
3. Stabilizing clay with sand dunes appears negative effect on CBR. The decrement in CBR continues with increasing sand content in the clay. Once 10% lime is added to the clay-sand mixtures, the CBR values increase. The CBR values of clay-sand-lime mixtures increase significantly with the increment of sand fractions. In the clay-sand dunes mixtures, the CBR values decrease as the decrement of porosity values. While the opposite trend occurs in the clay-sand dunes-lime mixtures, the CBR values increase with decreasing porosity values.
4. Adding sand only to the highly expansive clay cause also decrement in the USC. The USC has further decrements inducing lower values and more ductile behaviour with the increment of sand dosages compared to the non-treated clay. This is attributable to that the sand dunes are a cohesionless soil. When each clay-sand mixture is chemically stabilized by 10% lime, the USC and the porosity increase after 7 days curing time. All the clay-sand-lime mixtures imply UCS values greater than that of the non-treated soil except at using 50% sand fraction having approximate the same USC value of the non-treated soil. Moreover, the clay-sand-lime samples are stiffer and more brittle than the clay and clay-sand samples. The UCS trend increases when the sand contents are up to 30% in the clay-lime mixtures. Beyond the later sand content, the USC trend reduces. The USC values decrease as reducing porosity in both mixtures of clay-sand and clay-sand-lime after 7 days curing time.
5. The strength of the clay-sand-lime mixtures was also investigated at longer curing times. The reduction trend of USC beyond 30% sand fraction continues up to 21 days but with smaller rate and greater USC values. The USC trend after 21 days converts from reduction to increment. The incremental trend of USC become more pronounced after 56 days curing time especially for sand contents greater than 40%. Consequently, the greatest improvement occurs in the clay-sand-lime mixtures when using 50% sand dunes fraction. The later fraction raises the USC to 3.87 times of the stabilized clay by 50% sand fraction. The important enhancements in the strength of the clay-sand-lime mixtures are because of the long-term reaction (pozzolanic reaction). Consequently, increasing USC in the long-term reaction is an evidence to generate and increase the cohesion parameter of strength in the clay-sand-lime mixtures. Moreover, the pozzolanic reaction becomes more effective with the existence and increment of the sand dunes content and curing time.

Based on the above, stabilizing highly expansive clay with sand dunes has positive and negative influence in its swelling and strength properties, respectively. The existence of sand dunes beside the lime in the clay leads to remove swelling completely in the short-term as well as increasing strength and bearing ability with time in the long-term.

FUNDING

The author received no funding for this work.

DATA AVAILABILITY

This study does not generate new data and/or new computer codes.

CONFLICT OF INTEREST STATEMENT

The author certifies that there is no conflict of interest.

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