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ORIGINAL PAPER

The Impact of Moisture and Clay Content on the Unconfined Compressive Strength of Lime Treated Highly Reactive Clays

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Abstract This study aims to provide a thorough evaluation for the changes in the microstructure and evolution of strength of highly reactive clays that were treated with 7% lime over a period of curing time as a function of the mixing moisture content. Three series of testing were carried out on specimens with 100%, 85% and 75% of bentonite content and prepared with different moisture content of 10, 20, 30 and 40% above the corresponding optimum moisture content. Specimens of 100% bentonite were treated with 7% of lime, compacted to achieve a predetermined dry unit weight and cured at temperatures of 20 °C and 40 °C for up to 28 days whereas the specimens with 85% and 75% of bentonite content were prepared by the addition of sand and were cured at 20 °C for up to 7 days. Unconfined Compressive Strength tests and Scanning Electron Microscopy were conducted to observe the strength and the microstructural changes resulting from increasing mixing moisture content. California Bearing Ratio and Resilient Modulus were correspondingly determined based on correlations with the Unconfined Compressive Strength. The failure pattern was also studied to better understand the ultimate behaviour of lime stabilised clays. The results revealed that the strength of treated bentonite increased with the increase in the moisture content up to 30% above the corresponding optimum moisture content and with increasing the curing time and temperature. Nevertheless, substituting bentonite with sand on the specimen resulted in a significant reduction on the attained strength. Furthermore, the results of California Bearing Ratio and Resilient Modulus showed that values for both parameters are significantly enhanced with lime treatment. The microstructural analysis provided visual evidence to the improved strength in which the pozzolanic reaction was found to be significantly affected by the amount of moisture in the mixture. The results suggested that compacting lime treated expansive clays with moisture content moderately higher than the optimum moisture content would result in a significant enhancement to the attained strength over the period of curing.

Keywords Lime stabilisation · Water content · Pozzolanic reaction · Curing temperature · Expensive soil · Clay content

1 Introduction

Due to the substantial increase in the world's population, a growing demand for suitable land for the

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construction and development of new cities and infrastructures is imminent. This may lead to the requirement for construction on problematic soils e.g. expansive clays which is challenging owing to the potential volume change of such clay with a slight variation in the moisture content. It is anticipated that the volumetric changes would be exacerbated by the climatic changes. This causes a significant distress to the structural elements due to potential differential movement and may result to substantial adverse effects on the performance of structures (Khademi and Budiman 2016) and/or lead to the failure of the whole structure unless preventive measures are implemented. The degree of swelling and shrinkage is linked with the mineral composition of the expansive soils e.g. montmorillonite, illite and kaolinite (Schanz and Elsawy 2017). The implementation of preventative schemes e.g. partial replacement of surface ground layers, chemical treatment using lime, cement and ash and soil reinforcement is recommended so as to eliminate and/or minimize the adverse effects of potential volume change as well as to stabilise such expansive soils (Amhadi and Assaf 2018). Among the traditional stabilisation by chemical additives, lime is by far the most common owing to the economic and effectiveness considerations. Accumulated knowledge in the area of lime stabilization of expansive clays has broadened the range of applications of this technique and shown much advancement in the area of geotechnical engineering practice and research. Lime stabilization of soil was studied for decades (Hilt and Davidson 1959; Eades and Grim 1960; Miller et al. 1970; Bell 1996; Petry and Berger 2006; Nasrizar et al. 2010; Mohd Yunus et al. 2017; Zhu et al. 2018; Gallaway and Buchanan 1951; TRB 1987, Ismeik and Shaqour 2020). Generally, a consensus was reached that lime treated materials exhibit improved characteristics in comparison with those measured on the untreated soil. These characteristics include decreasing the plasticity index, volume change and maximum dry density and strength. Several studies, see for instance (Zhu et al. 2018; Bell 1988; Bagoniza et al. 1987; Lawton 2001; O'Flaherty 2002; Reeves et al. 2006; Amaya et al. 2019), attributed the improved geotechnical characteristics of lime treated expansive clays to four distinct reactions called; cation exchange; flocculation and agglomeration, pozzolanic reaction and lime carbonation. Cation exchange takes place immediately if adequate water is presented resulting in the dissociation of the hydrated lime into Ca^{++} and OH^-. On the surface of clay particles, the ions of Ca^{++} exchange with cations altering the properties of the water films on the particles. Cation exchange affects the flocculation and agglomeration of the particles causing a considerable change in the soil texture which in turn modifies the Atterberg limits and the compaction properties due to the exothermic reaction produced by the hydration of calcium oxide (Amaya et al. 2019). This also causes molecular interactions where expansive clays have a molecular structure similar to some polymers and possess plastic properties. The structure can trap water between its molecular layers, causing volume and density changes (Naveena et al. 2017). Clays typically have positive charges on their edges and negative charges on their faces, calcium ions from lime attach to the faces of the clay particles flocculating the clay structure. When the changes in the soil texture take place, there is an apparent reduction in the clay percentage and a corresponding increase in the content of coarse particles (Kumar et al. 2007).

The reactions of lime with the three essential minerals of clay, which are montmorillonite, kaolinite and illite, start by the replacement of existing cations between the silicate sheets with Ca^{++}. The chemical reaction of lime with clay minerals (aluminates and silicate), in presence of water is referred to pozzolanic reaction and forms cementitious compounds called Calcium Silicate Hydrate (CSH) and Calcium Aluminate Hydrate (CAH) that have long-term effects on the volume stability and strength. The pozzolanic reaction continues as long as the high pH condition is maintained which increases the solubility of the alumina and silica present in the soil (Elkady and Shaker 2018). The solubility of the mentioned chemical elements depends on the mineralogy composition of clay. Ali and Mohamed (2019) found that bentonite reacted swiftly with hydrated lime resulting in a remarkable improvement in the strength with curing time and temperature, whereas the treated kaolinite showed that the strength gain entered in an inactive phase in which no improvement in strength was observed over time particularly at 20 °C but with raising the curing temperature to 40 °C, the inactive phase was shortened to only 3 days. It was suggested that the accumulation of calcium cations on the surface of kaolinite led to obscuring the mineral surfaces from the alkaline environment. This accumulation resulted in a delay in the release of Alumina and Silica subsequently, the formation of cementitious compounds is delayed. Other studies e.g. Bell (1993) and Maubec et al. (2017) based on results on specimens cured for more than 50 days at 50 °C, reported that long-term improvements continue to occur which was dominated by the pozzolanic reaction.

Carbonation occurs when the carbon oxide, from the rainwater and air, reacts with the lime converting free magnesium and calcium oxides and hydroxides into calcium carbonate or magnesium carbonate instead of the cementitious binding compounds. Although some strength might be gained, the effect of cementing action is weakened leading to an overall reduction on the gained strength (Cizer et al. 2006). The aforementioned reactions are widely reported, but lack of consensus led to many issues being remained as points of controversy. For example; the timescale over which the aforementioned mechanisms take place and, more importantly, whether the reaction mechanisms occur consecutively or simultaneously, are less well established (Ali and Mohamed 2019; Boardman et al. 2001). There has been an inconclusive debate about these issues. (Haas and Ritter 2018; Di Sante et al. 2014; De Windt et al. 2014) discussed that after mixing and compacting the soil, cation exchange is completely ended and pozzolanic reactions are initiated due to that the hydration of lime increases the pH value of the soil in a few hours. The pozzolanic and carbonation reactions may occur concurrently if the carbon oxide reacted with the lime. Whereas, Diamond and Kinter (1965) suggested that adsorption and reaction of lime at the clay surface gives rise to immediate local pozzolanic reactions at these surfaces. This lack of agreement may be attributed to the complexity of the clay nature and the possibility for different mechanisms to take place in different minerals and time-scale. It is imperative to note that all the aforementioned studies were performed on clay-lime mixtures that were prepared at a particular moisture content which was close to the plastic limit.

The behaviour and treatment of expansive soils is highly influenced by the moisture conditions (i.e. available water), especially if the soil comprises highly reactive clay e.g. sodium bentonite. In lime-soil stabilization, water is a critical player due to its necessity as a medium to mobilize the ions of calcium that exchange with cations at the surface of the clay increasing the pH value of the soil system. Furthermore, where the soils have a great affinity for water, the hydration of the stabilizer may be restricted which can inversely influence the treatment process and the achieved ultimate strength of the treated soil (White et al. 2005). Nevertheless, climatic changes resulting in heavy rainstorms and subsequent flooding are more likely to occur frequently in future more than in the previous decades. It is often the case that specimens for the determination of strength and other geotechnical properties of expansive clay are prepared at a particular moisture content and dry density which represent either the in-situ conditions or desirable conditions for controlled engineering works. It is therefore of paramount importance that investigative studies are conducted assessing the effect of potentially increased water content due to heavy rainstorms scenarios on lime treatment practice of highly reactive clays.

Limited studies are available in the open technical literature for the strength of lime stabilised expansive clays as a function of increasing moisture content. Petry and Berger (2006) investigated the impact of water content on the strength of lime treated clays by testing three different clays with a narrow range of plasticity index (PI) of approximately 20% up to 50%. It was concluded that lime treated soils achieved their greatest Unconfined Compressive Strength (UCS) at or near Optimum Moisture Content (OMC). Specimens with plasticity indices of 28% and 22% attained significant strength gain when they were compacted with moisture content of 2% less than the OMC in the dry side. The highly plastic clay with PI of 51%, however, quickly lost strength when compacted at the dry side of the OMC but benefited from being compacted in the wet side of the OMC. These findings contradicted the research outcomes by Fossberg (1965), Ramesh and Sivapullaiah (2011)_ENREF_54 who used soils rich in montmorillonite with PI of 42%, 51.4% and sandy clay with PI of 24% respectively. These studies reported a general trend of increase in the UCS values when the specimens were compacted with low moisture content. It was noted that no in-depth analysis for the increase in strength was provided. Govindasamy et al. (2017) experimented the lime treatment of clays with PI of 12.3% and attributed the increase in strength to the suction pressure in the soil due to being partially saturated. Meniscus water is formed bridging the tiny gaps between neighbouring particles and resulting in evolution of negative pore water pressure and apparent cohesion. With further increase in the available water, the erroneous attractive forces induced by the high value of suction pressure lose its effect resulting in a loss of strength. Nasrizar et al. (2010) examined a clay type with a high plasticity of 55% and showed that specimens compacted at the dry side of the OMC exhibited less strength than that attained when the specimens were prepared with water content in the wet side of the OMC. After 28 days, the strength of the tread specimens compacted at the wet side of OMC was slightly higher than that compacted at the OMC. These results were in agreement with those reported earlier by Petry and Berger (2006). The water adsorption capacity of clay minerals is the main reason for increasing the strength of highly plastic soils with the increase in the water content. This view is supported by the study of Bell (1996) who stated that the highest gain in strength occurs when the mixing water content is in excess of the OMC. Furthermore, the clay treated with higher content of lime is more sensitive to the variation of water content. Due to the large surface area of the clay particles, significant interactions take place between intermixed materials which improve their strength (Govindasamy et al. 2017). The surface area of bentonite clay is higher than that of kaolinite clay, it is therefore more likely that the lime would react with the bentonite particles at a higher rate leading to a considerable reduction in the surface area of bentonite and a relatively higher strength immediately after compaction (Ali and Mohamed 2019). In the case of kaolinite clay, the strength improvement is mainly contributed to the mobilization of attractive forces between the kaolinitic particles, which leads to increased flocculation, and hence, higher strength; whereas in the case of montmorillonite, the contribution come from the viscous resistance as contributed by the diffuse double layer (Nagaraj and Suresh 2018). Montmorillonite and kaolinite materials respond more quickly to strength increase, although the final strength achieved is greater in kaolinitic particles after a very long period of time (Bell 1988, Maubec et al. 2017).

Results attained by Tulloch et al. (1970) indicated that at low moisture content, increasing the clay content resulted in a considerable reduction in the strength, whereas, at high moisture content, increasing the clay content resulted in an increase in the strength of the lime treated specimens. A plausible explanation for this fundamental disagreement is that there is sufficient water for the reactions to take place when low water content is combined with a low clay content resulting in strength gain. In contrast, in specimens with low moisture content and high clay content it is likely that most of the water is adsorbed by the clay particles leading to an insufficient amount of water left for the lime-clay reactions to be completed. Le Runigo et al. (2011)'s work offered another explanation by which the cementitious material precipitation is probably more significant in the case of low density soil due to existing large pore spaces. The developed strength in lime-soil systems depends on, to a great extent, the space of the voids occupied by the cementitious compounds (Diamond and Kinter 1965). The above aforementioned studies were carried out on clays with a narrow range of plasticity index and moisture content. Nevertheless, no consensus was reached on the effect of the moisture content on the behaviour of lime treated clays.

As expansive soils are prone to significant volumetric changes, pavements built on them are subjected to accelerated deteriorations. This adversely affects the pavement longevity which leads to the requirement for costly remedial measures. An improvement in the California Bearing Ratio (CBR) and Resilient Modulus (M_r), which are always desirable phenomena in pavement performance can be achieved by stabilizing the underlying expansive clay subgrade with hydrated lime. The subgrade must be able to support loads transmitted from the pavement structure. A subgrade having a CBR of 10 or greater is considered necessary and can support heavy loads and repetitious loading without excessive deformation (Schaefer et al. 2008). The higher the value of CBR of a particular soil, the more strength it has to support the pavement. This means that a thinner pavement structure could be required to support the pavement. Many studies investigated the effect of lime on the CBR (Amadi and Okeiyi 2017, Kavak and Akyarlı 2007, Muntohar and Hantoro 2000). From the reported results, an increasing trend in the CBR values was observed. However, the increase could be due to availability of sufficient lime to initiate the pozzolanic reactions. As the curing time increases, the cementitious compounds forms, and the bonding effect causes an increase in the observed CBR values. The design of flexible pavement is normally based on M_r. Bhuvaneshwari et al. (2019) studied the effect of lime addition on the resilient modulus of expansive soil and found that lime treated soils exhibit higher resilient modulus values comparing with those that were untreated.

Despite the large number of studies, a better understanding of failure modes and its relation to treatment of soils has not been developed (Güneyli and Rüşen 2016; Tang et al. 2016; Li et al. 2017). Various failure mechanisms can be observed when lime treated clay specimens are loaded to failure which are associated with different modes of deformation ranging from brittle to ductile behaviour. The nature of the deformation is dependent on the prevailing soil conditions such as the moisture content and texture (Spoor and Godwin 1979; Hatibu and Hettiaratchi 1993). The brittle behaviour is characterized by a dilative response and sudden failure whereas the ductile deformation is featured by a contractive response and gradual deformation to failure (Nygård et al. 2006). Some researchers found that lime treatment contributed to the brittle failure characteristics of clays that led to a rapid and great loss in strength when failure occurs (Cai et al. 2006). Tagar et al. (2014) pointed out that the brittle failure occurs in moist soils, with water contents not exceeding the plastic limit. This desaturation of the soil leads to its brittleness (Tang et al. 2016). However, no systematic assessment of the failure pattern has been conducted on specimens of lime treated clays at varying amounts of the moisture content.

Based on the above critical review of the technical literature, it seems reasonable to conclude that further investigations are needed for the effect of increasing moisture content on the lime treatment of highly reactive clay e.g. sodium bentonite to address the conflicting opinions concerning its role in the process and discussing the primary reasons that caused observed change in strength. In this paper, a programme of research was designed and carried out to investigate the engineering properties of lime treated highly reactive clays e.g. amount of bentonite material as well as the microstructure changes that occur as a function of changing the moisture content in the mix. Specimens were prepared at a predetermined dry unit weight whilst moisture content was systematically increased above the OMC up to reaching full saturation. Three different materials with bentonite content of 100%, 85% and 75% were utilised by the addition of fine sand. The reactive clays were then mixed with 7% lime content and tested under different conditions of moisture content, curing time and temperature. Specimens, without sand, were cured at two different temperatures of 20 °C and 40 °C for a period of time that lasted up to 672 h (28 days) whereas specimens of bentonite–sand mix were cured for up to 168 h. The results were discussed to explore the effect of using high water contents during the stabilization process of expansive clays with lime.

2 Materials

A highly reactive expansive clay utilised in this study is a commercially available sodium activated bentonite. The bentonite has been milled and air classified to give a consistent fine powder.

Table 1 provides the chemical analysis of the utilised bentonite which was supplied by Potclays Ltd., UK. The data illustrated that almost 94% of the bentonite is in the form of silicon dioxide and aluminium oxide. The geotechnical properties of the untreated clays are summarised in Table 2. Consistency limit tests were carried out as prescribed in BS1377-2 (1990). It is clear that the sodium bentonite has an extremely high liquid limit of 330% and plasticity index of 287% belonging to a very reactive clay.

Commercially available hydrated lime which consists of 97% of Ca $(OH)_2$, supplied by Lafarge Cement Ltd**.,** UK, was used in this study. Due to the inherent swelling properties of the bentonite minerals, adding water to the bentonite resulted in a thick sludge preventing the pH measurements, so

Table 1 Chemical analysis of the utilised bentonite

Clay elements and percentage (%)								
SiO_2	Al_2O_3	LOI*	Fe_2O_3	MgO	Na_2O	Trace	CaO	FeO
63.02	21.08	5.64	3.25	2.67	2.57	0.72	0.65	0.35

*Loss on ignition representing organic matter content

Table 2 Physical properties of the utilised clays

Material type	Property	Value
100% Bentonite	Shipped water content, %	10.6
	Specific Gravity	2.6
	Liquid limit, %	330
	Plastic Limit, %	43
	Plasticity index, %	287
	Maximum dry unit weight, kN/m^3	11.2
	Optimum moisture content, %	40
85% bentonite + 15% sand	Maximum dry unit weight, kN/m^3	12.58
	Optimum moisture content, %	35
75% bentonite + 25% sand	Maximum dry unit weight, kN/m^3	12.6
	Optimum moisture content, %	36
100% sand	Maximum dry unit weight, kN/m^3	16.5
	Optimum moisture content, %	8.3
	Coefficient of uniformity, C_u	1.89
	Coefficient of curvature, C_c	1.02
	Effective grain size, D_{10}, mm	0.18
	D_{30} (mm)	0.25
	Medium grain size, D_{50}, mm	0.32
	D_{60}, mm	0.34
	Friction angle, degree	29
	Cohesion, kN/m^2	0

it was practically difficult to determine an Initial Lime Consumption (ILC) according to BS1924-2 (1990). Similar observations were previously made by Boardman et al. (2001) and Ali and Mohamed (2017). Therefore, in this investigation, 7% of hydrate lime (calcium hydroxide) was selected and added by dry weight of highly reactive clays to induce pozzolanic reactions in the clay as recommended by Ali and Mohamed (2017) and suggested by Ingles and Metcalf (1972) who reported that the addition of 3–8% lime is required for the stabilization of heavy and very heavy clays. Two other materials were developed by adding fine sand at a ratio of 15% and 25% to bentonite to investigate the effect of the clay content on UCS values when specimens were prepared with different moisture content. The experimentally acquired data for the physical and mechanical properties of the used sand are presented in Tables 2. In addition, the particle size distribution of the sand used and compaction curves for different clay materials are presented in Fig. 1 and Fig. 2 respectively.

3 Experimental Programme and Techniques

In order to design a comprehensive testing programme, it was important first to identify the compaction characteristics of the three different materials used in this research study. The results of the compaction tests on the three different materials that were prepared based on 100%, 85% and 75% of bentonite are shown in Error! Reference source not found. It should be noted that the compaction data was achieved using the purpose-made compaction mould and hammer by Ali and Mohamed (2018) to make significant saving on materials, effort and time which is shown in Fig. 3. The results of the optimum moisture content and maximum dry unit weight obtained are summarised in Table 2. The dry unit weight increased and the optimum moisture content decreased with the addition of fine sand. The maximum dry unit weight of pure bentonite, 85% of bentonite mixed with 15% of sand and 75% of bentonite mixed with 25% of sand are 11.10 kN/m^3 to 12.60 kN/m^3 and 12.58 kN/m^3 respectively. The maximum dry unit weights are achieved at corresponding moisture contents of 40%, 36% and 35% respectively as reported in Table 2. The

Fig. 1 Particle size distribution of sand

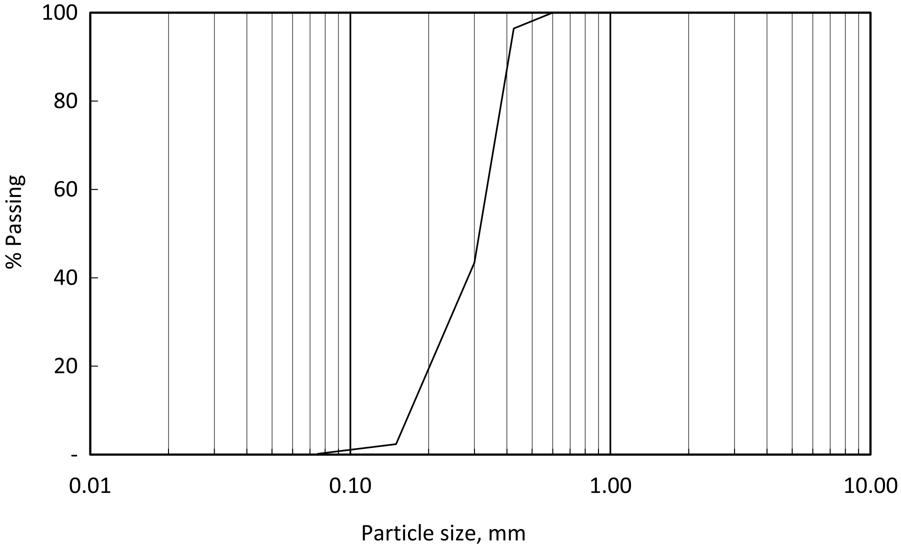
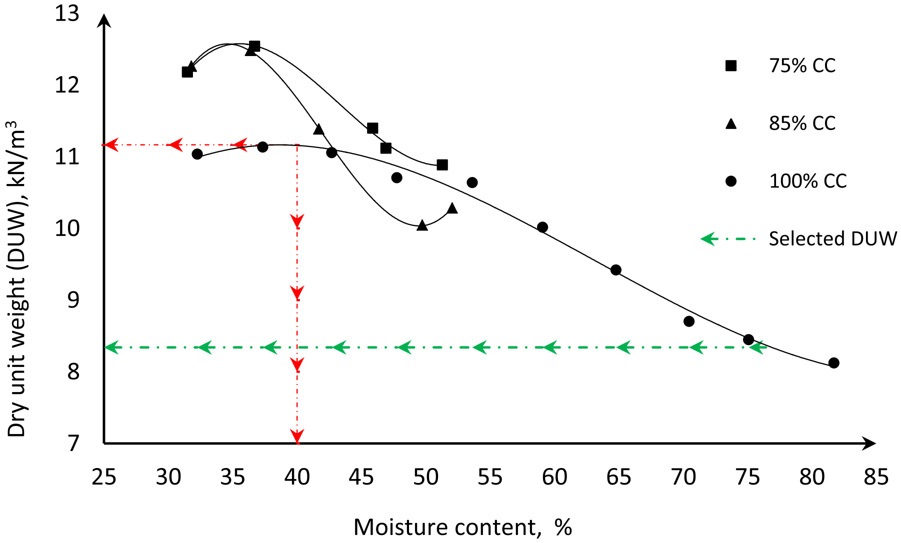


Fig. 2 Maximum dry unit weight and optimum moisture content of clay materials



higher OMC of the bentonite resulted from the high water absorption capacity of the clay whilst the slight improvement in the dry unit weight of bentonite–sand mixture could be attributed to the packing of sand and clay particles due to improvement in the gradation of the mixture.

In order for the effect of moisture content to be assessed simulating the impact of increasing moisture content due to rainstorm events and subsequent reduction in unit weight on the strength evolution of lime stabilised clays, the moisture content was varied in the wet-side of the compaction curve up to reaching the state of being fully saturated. The range of moisture content in the present research study was carefully selected whilst keeping the unit weight of all specimens constant. A desired lower Dry Unit Weight (DUW) was selected from the compaction curve which was 8.34 kN/m^3 and kept fixed in this research study for a robust and rigorous assessment for the effect of increasing moisture content on the strength evolution to be made. The variable and fixed parameters in each series of tests are presented in Table 3. Specimen preparation procedure was carefully selected after performing a number of preliminary trials in which lime was added to dry and wet clay. The latter was found to produce specimens with

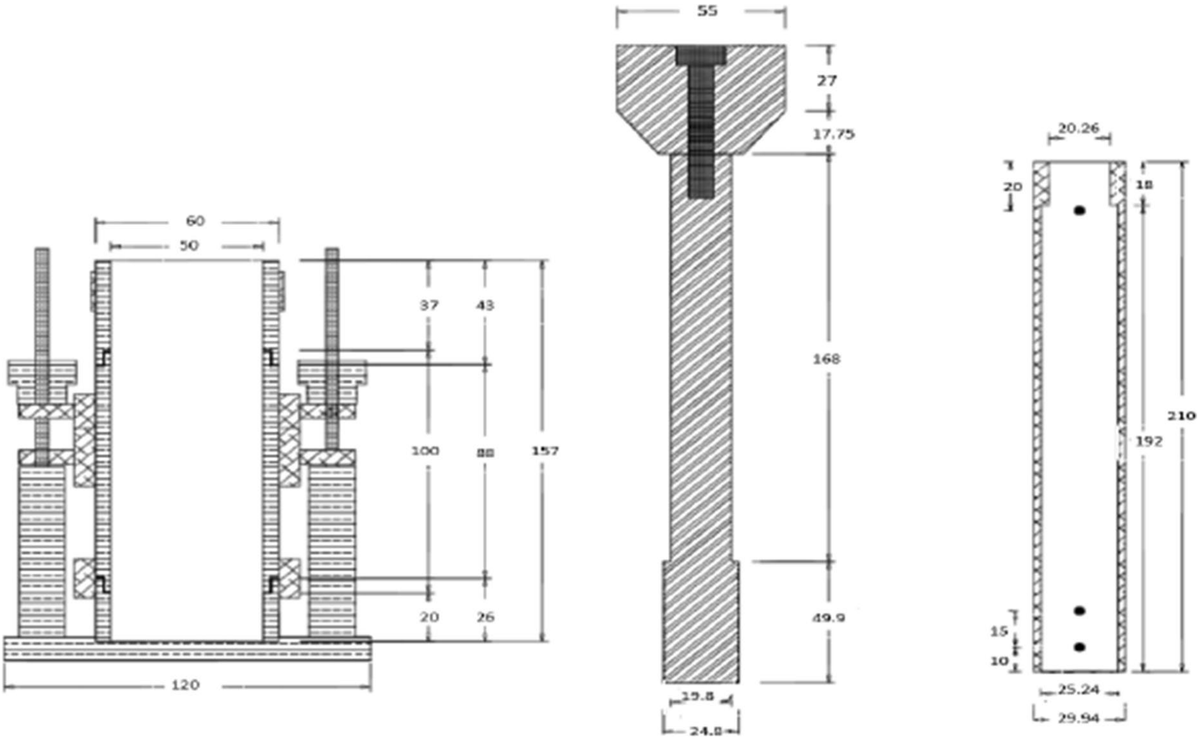


Fig. 3 Dimensions of the compaction tools in mm

Table 3 Testing programme

Test	Parameters	
	Variables	Fixed
Unconfined compressive strength	MC = OMC + 10%, OMC + 20%, OMC + 30% and OMC + 40% T = 20 °C and 40 °C LC = 0 and 7% CT = 0, 3, 6, 12, 24, 72, 168 and 672 h CC = 100%, 85% and 75%	$Y_d = 8.34$ kN/m^3
Scanning electron microscope	MC = OMC + 10%, OMC + 20%, OMC + 30% and OMC + 40% LC = 0 and 7% CP = 0 and 672 h at 20 °C and 72 h at 20 °C and 40 °C	$Y_d = 8.34$ kN/m^3

where *CC* clay content, *CT* curing time, *LC* lime content, *T* temperature, *MC* moisture content and Y_d dry unit weight

obvious white clusters of lime within the clay matrix which indicated that lime is not uniformly distributed in the specimen. Consequently, it was decided to initially prepare dry mixtures after which water was introduced to ensure the preparation of uniform mixtures. To prepare the specimens in accordance with different test conditions, predetermined amounts of dry bentonite and bentonite–sand mix were mixed in a mechanical mixer with 7% of hydrated lime by weight. The mixing process continued until an even distribution of lime in the mixture was attained which was recognisable by the uniformity of mix colour. The lime-clay mixtures were then mixed manually whilst gradually adding water to prepare the specimens with predetermined water contents. Lime treated clay specimens were prepared with moisture contents of 10, 20, 30 and 40% above the corresponding OMC.

Unconfined Compressive Strength tests were carried out for investigating the evolution of the strength of lime stabilised reactive clays due to its simplicity and cost effectiveness (Güneyli and Rüşen 2016). The UCS tests were conducted in compliance with British standards BS1377-7 (1990). In this study, specimens of untreated soils and lime treated bentonite and bentonite–sand mixtures were prepared with different moisture contents as illustrated in Table 3. All specimens were compacted in five layers under static load to achieve the desired dry unit weight using a purpose made mould and plungers. Figure 4 shows a schematic drawing of the developed mould and plungers with dimensions. Each layer was prepared with the same quantity of mixed materials e.g. clay, sand, lime and water. One of the tall plungers was inserted into the mould then one-third of the mixture was poured carefully into the mould and levelled by a quick shaking and the other tall plunger was pushed into the mould. Promptly, the mould was compressed using the hydraulic jack to form the middle part of the specimen. After that, the two tall plungers were removed. The second third weight of the mixture was divided into two equal portions. The first part was poured into the top of the mould, followed by placing the medium-size plunger. Afterwards, the mould was turned upside down, and the other part of the second third portion was poured into the mould. The mould was compressed using the medium-size plungers. To compact the full height of the specimen, the final two layers were compressed in the mould in a similar procedure using the short plungers. Finally, the specimen was extracted from the mould. Force was applied as required to compress the mixed materials to produce a layer of a particular volume where any additional force is transmitted to the mould shaft through the head of the plunger. This method of preparation was proven to produce specimens with higher uniformity of density which resulted in a significantly reduced discrepancy in the measured UCS (see, Saad et al. (2012) and Ali and Mohamed 2017). Of note, it was found practically difficult to prepare lime treated bentonite–sand specimens with moisture content of 30% and 40% above the corresponding OMC since the prepared wet mixes were not workable. For each testing condition, three identical specimens were prepared and tested to ensure high accuracy and reliability of the generated data. Measurements for the specimen's weight, diameter and height were recorded once specimens were extracted from the compaction mould. The specimens were wrapped by a cling film

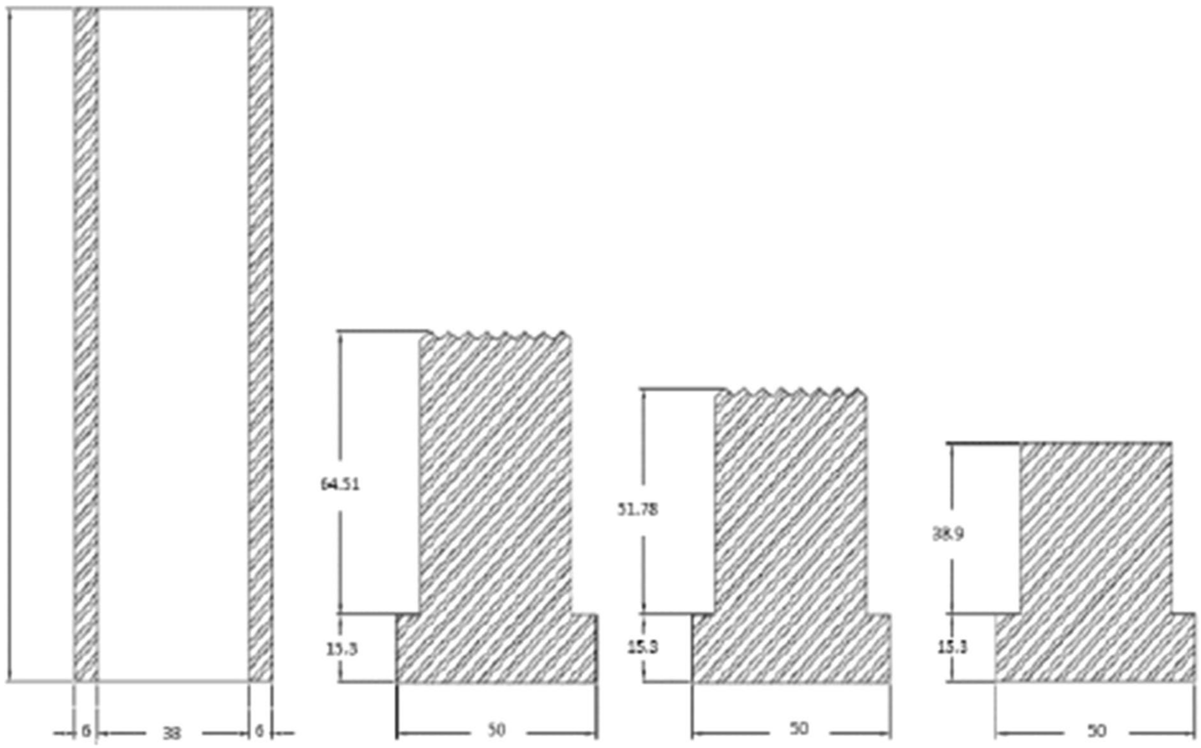


Fig. 4 Dimensions of compaction equipment for UCS specimens in mm

and stored in double sealed bags upon extraction from the compaction mould to preserve the moisture content and to prevent carbonation. The specimens were then left in an environmental cupboard at a controlled temperature of 20 °C or 40 °C and 90% humidity to cure for periods of time of 3, 6, 12, 24, 72, 168 and 672 h. This relative humidity was adequate to aid the prevention of moisture loss during the curing time Prior to testing, measurements of the weight, diameter and height of cured specimens were taken and compared with those recorded at the earlier stage of preparation e.g. immediately after compaction. This comparison revealed that no change in the size of the specimens nor in the moisture content occurred over the period of curing. All specimens were tested at an axial movement rate of 1 mm per minute until failure.

Scanning Electron Microscope (SEM) tests were performed on dry specimens to reveal useful information about the crystalline structure of lime stabilised clay specimens. A number of approaches were found to prepare specimens for SEM testing include fracturing, grinding and peeling (Bhuvaneshwari et al. 2014, Ural, 2016, Mohd Yunus et al. 2017). Soil specimens with high water contents are usually fragile when dried and can easily be damaged or destroyed with fracturing (Shi et al. 1999), Thus, these techniques are not recommended for preparing SEM samples for soils with high water contents. In order to minimise microstructural changes, small pieces of the dried untreated and treated specimens were cautiously taken and placed on a metal stud and coated with gold before scanning. The aim of the coating is to increase the signal and surface resolution during scanning. Images were taken at 5000 × magnification for the maximum possible clarity.

4 Results and Analysis

UCS results on lime treated highly reactive clays are presented and discussed to evaluate the effect of initial mixing moisture content over a period of curing time and different environmental temperatures. To aid the discussion, the UCS data have been supplemented by the scanning electron microscope analysis. In addition data for California Bearing Ratio and Resilient Modulus were generated to enable assessing impact of lime treatment on the design of road construction.

4.1 Unconfined Compressive Strength Evolution

Results for the evolution of strength on compacted untreated bentonite and 7% lime treated bentonite specimens are presented in Figs. 5 and 6 for curing temperature of 20 °C and 40 °C respectively. The UCS values of untreated specimens showed a considerable effect for the initial water content on the attained UCS immediately after compaction. The

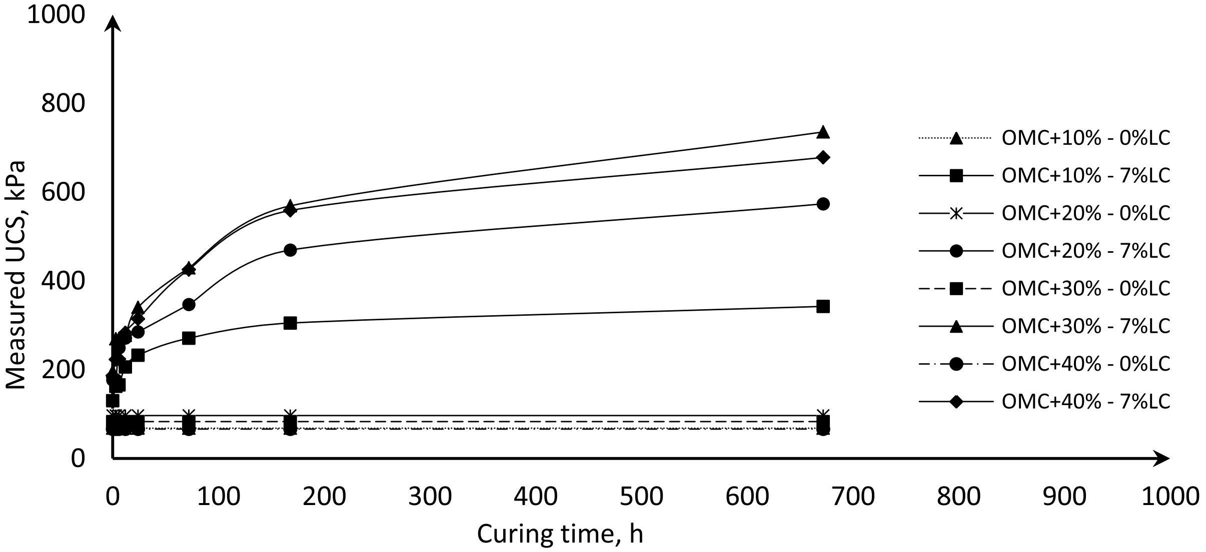


Fig. 5 Evolution of strength with curing time on untreated and lime treated bentonite cured at temperature of 20 °C

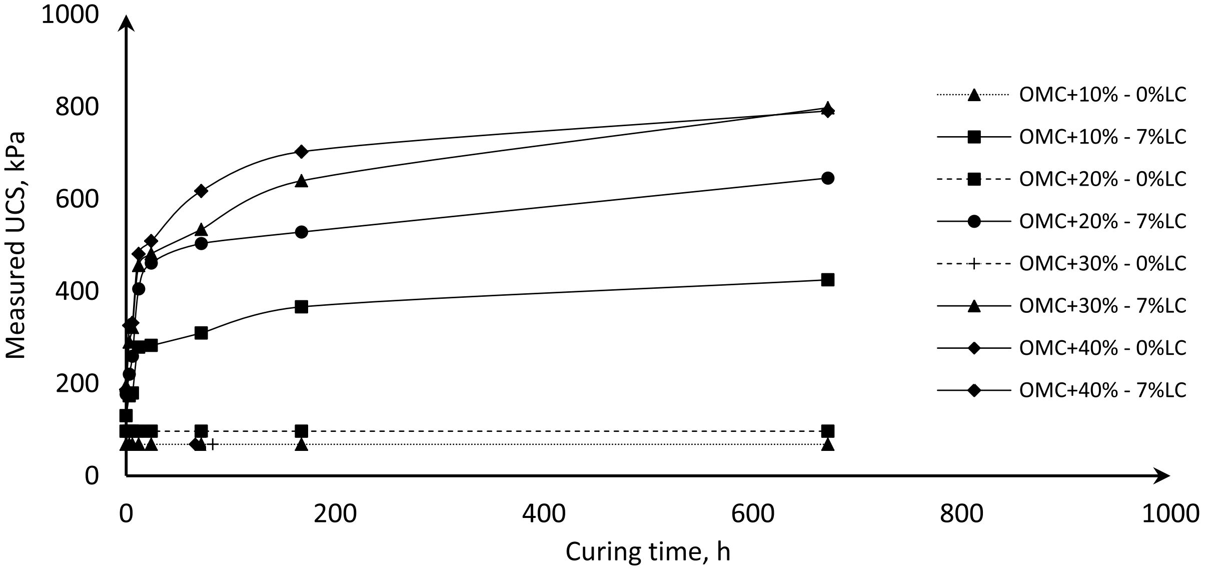


Fig. 6 Evolution of the strength with curing time on untreated and lime treated bentonite at curing temperature of 40 °C

observed UCS values varied between 65 and 100 kPa. The results indicated that maximum compressive strength was observed when the bentonite powder was mixed with a moisture content of 60% which is 20% above the OMC value obtained from the compaction data. This could be attributable to the distribution of pore voids within the specimen. Adding more water led to weakening the strength of compacted bentonite. It is also noted that there were no changes in the measured UCS of pure bentonite irrespective of the period of time after compaction. By decreasing the amount of water, the radius of the meniscus formed at the surface decreases which in turn increases the suction head and the ability of the clay to resist greater stresses (Ridley 2015). Figure 5 also shows data for the bentonite specimens that were treated with 7% lime at different moisture content ranging from 50 to 80%. The data clearly showed a remarkable increase in strength by almost 100% when the lime treated specimens were tested immediately after compaction. In particular, the specimens prepared with a moisture content of 10% above the corresponding OMC experienced an increase of 91% which is similar to earlier findings by Bhuvaneshwari et al. (2014). With further addition of water, the strength showed further increase reaching a maximum increase of 135% when the specimens were prepared at a moisture content of 30% above the corresponding OMC value. This revealed that addition of more water during the preparation of lime treated bentonite is favourable when the specimens were tested immediately after compaction. Results of lime treated bentonite specimens cured for a period of time up to 672 h (28 days) at 20 °C and 40 °C are plotted in Figs. 5 and 6. It can be seen clearly from the figures that the rate of increase in the strength was more rapid during the initial period of curing time rather than at the later stage of curing. These results suggested that the rate of strength gain followed two stages processes called fast and equalisation stages which were previously reported by Ali and Mohamed (2018) For example, the rate of increase in the strength gain on the specimen prepared with moisture content of 10% above the corresponding OMC and cured at 20 °C for the first 12 h was 6.3 kPa/h, whilst the rate of strength gain dropped to 0.4 kPa/h for a curing time from 72 to 168 h. Specimens cured at 40 °C showed higher strength gain of 12.4 kPa/h and 0.6 kPa/h during the fast stage (0–12 h) and stabilisation stage (72–168 h) respectively. These results revealed that increasing the initial moisture content had a favorable effect on the strength gain of lime treated bentonite specimens. The improvement in strength gain could be attributed to the availability of water above the amount of water in the form of absorbed water to facilitate the chemical reaction between lime and clay particles at a fast rate. The earlier research study by Shaw (1960) reported that increasing the moisture level in the soil improved the rate of reaction between lime and clay. Since the lime treated bentonite specimens were compacted at a relatively low density leading to the existence of substantial voids which in turn would provide ample space for the development of diffuse double layer. The availability of water improves the migration of ions around the clay particles which enables the evolution of cementitious compounds occupying the void space and bridging the gaps between the particles instead of the water (Beetham et al. 2015). Diamond and Kinter (1965) reported that the developed strength in lime treated clay systems not only depends upon the type of formed cementitious compounds but also, to a great extent, on the size of voids occupied by the cementitious compounds. The precipitation of cementitious compounds is more significant for the stabilisation of low density soils due to the amount and size of pore voids (Le Runigo et al. 2011). The cation exchange process makes the clay particles to flocculate by replacing calcium Ca^{++} ions in the soil solution with other common cations from the clay repressing the double layer, thus decreasing the repulsive forces between the clay particles. This leads to a net attraction, especially between negatively charged faces and positively charged edges of adjacent particles, developing card-house structure. Removal of these ions from the pore solution leads to spreading the double layer again out, increasing the repulsive forces between the particles, weakening the particles and reducing their size, and eventually the system is deflocculated (Kumar et al. 2007). The results for lime treated bentonite and cured at higher temperature are clearly revealed that distinct relationships were observed as a function of the initial water content over the curing period and curing temperature experiencing different degrees of strength gain. The improvement could be due to the completion of chemical reactions at faster rate where more lime was available for the pozzolanic reaction as well as the availability of pore water to facilitate such reaction (Ghorbani et al. 2019). The strength gain in the lime treated bentonite cured at 40 °C was therefore higher than those cured at 20 °C. The progress of pozzolanic reaction is reported to occur at a higher rate at high temperature. The results suggested that sufficient reactive silica was available in the bentonite to continually react with the lime over the period of curing time assigned in this study. In addition, curing at higher temperature accelerated the lime—clay reactions (Al-Mukhtar et al. (2010) and increased the rate of diffusion which is dependent upon the degree of water saturation (Barker et al. 2007). Increasing the amount of available water in the voids due to mixing at higher degrees of saturation enhanced the thermal flow and diffusion processes. The high thermal conductivity of water leads to the transfer of heat between various areas of the lime treated bentonite which in turn increases molecular excitement and accelerates the migration of ions. As a result, the rate of chemical reactions would speed up leading to a higher strength gain. It is vital to note that if the lime treated clays dries out at any stage, then the chemical reactions would cease due to the curtailment of the transportation process (Bell 1988, Beetham 2015, Barker et al. 2007).

The UCS results on untreated and treated specimens with different moisture contents of 10, 20 and 30% above OMC and bentonite content of 100, 85 and 75% by the addition of sand are presented in Fig. 7a, b and c. It can be seen in Fig. 7a that the strength of lime stabilised specimens recorded a degree of improvement with the increase in the moisture content on specimens of pure bentonite irrespective of the curing time. However, on specimens that incorporated percentage of sand, the maximum strength gain was observed on specimens with 85% bentonite and prepared with moisture content of 20% above the corresponding OMC value. Specimens with bentonite content less than 100% experienced a considerable reduction in the strength with the increase in the moisture content. The observed behaviour could be attributed to; i. less lime-clay reactions due to the reduction in the amount bentonite particles because of increasing the sand content, ii. increased excess pore water due to the reduction in the adsorbed water by the sand particles leading to extra water being available in the pore voids, and iii. a considerable enlargement of the pore voids as a result of increasing the sand content in the specimen whilst maintaining the same dry unit weight as shown by the images in Fig. 8 for specimens with different bentonite content and prepared with moisture content of 20% above the corresponding OMC. Water absorption in the lime-treated specimens diminishes with the increase of sand content (Temga et al. 2018). In addition,

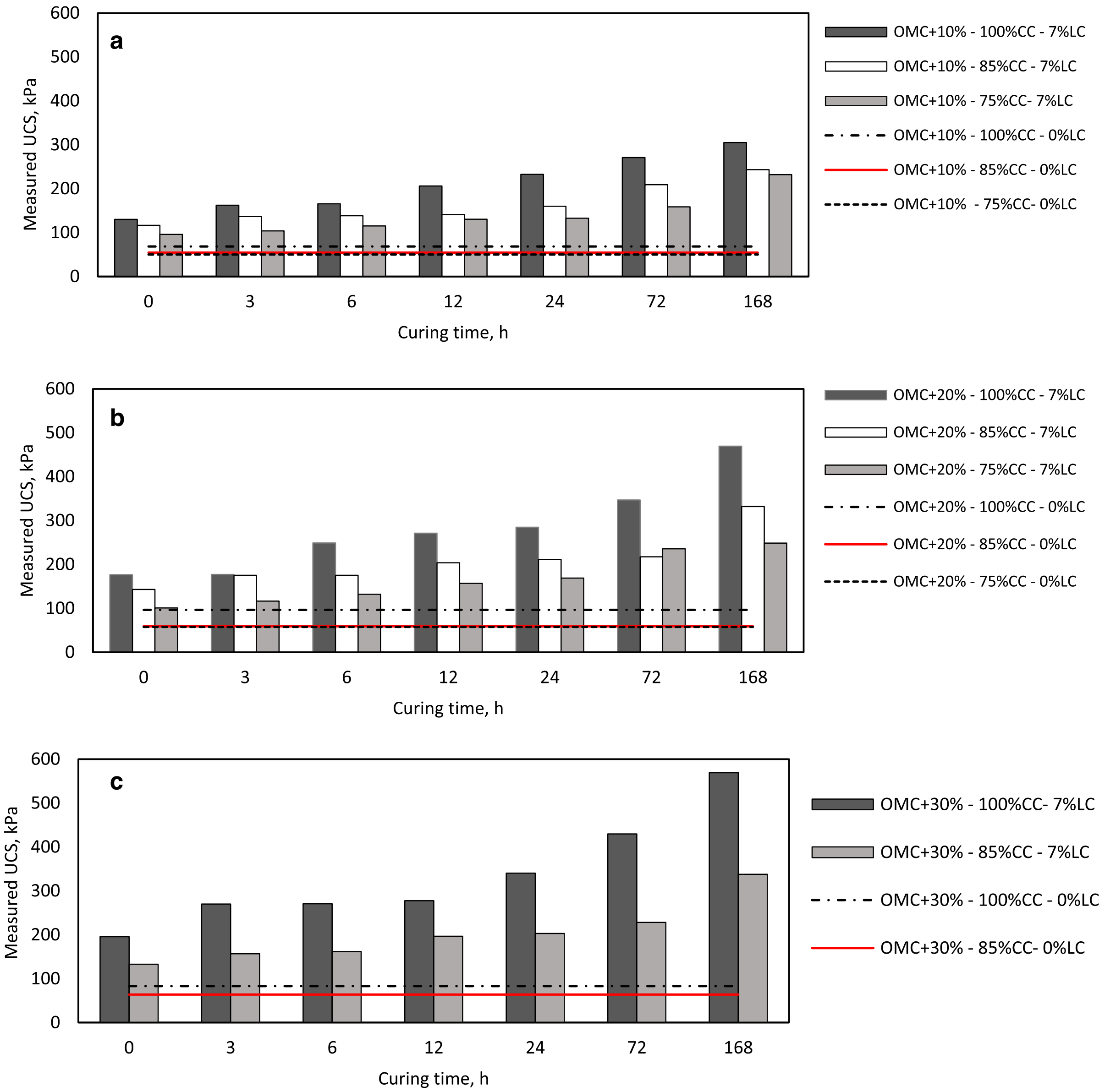
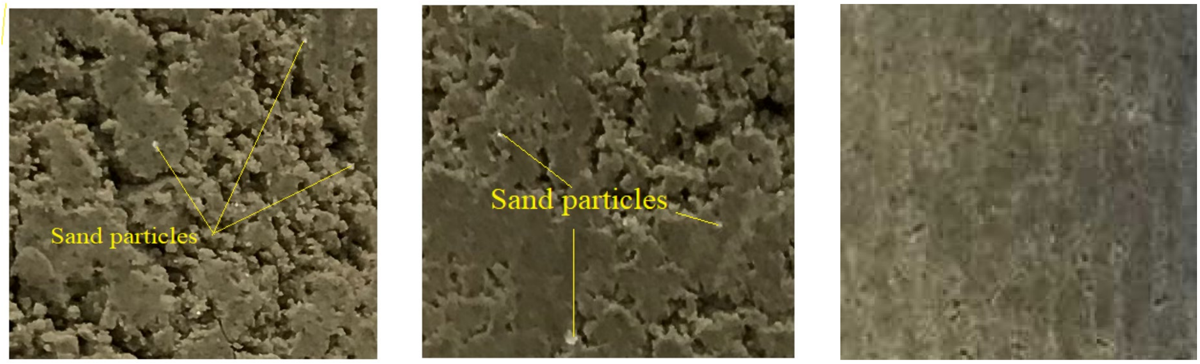


Fig. 7 UCS for various bentonite–sand mixtures with developing water contents

adding more sand to the specimens could lead to less cohesion between the particles in the mixture which reduced the strength of the treated specimens and decrement of strength with the increment of the percentage of sand. Similar observations for the reduction in strength were reported by Schanz and Elsawy (2017) when incorporating sand into the mixture. Despite observing reduction in the strength gain at a higher moisture content of 40% above the OMC value, the strength attained on lime treated mix of bentonite and sand was still considerably higher than that achieved on untreated specimens. The curing period has a significant effect on the improvement in the strength of expansive bentonite–sand-lime mixtures which could be attributed to the pozzolanic activity as long-term reactions being time bound. The results suggested that the effectiveness of lime treatment on bentonite–sand mix soils depends on several factors e.g. mixing moisture content, sand content and curing time.



MC = OMC + 20 %
CC = 75 %
CT = 6 h

MC = OMC + 20 %
CC = 85 %
CT = 6 h

MC = OMC + 20 %
CC = 100 %
CT = 6 h

Fig. 8 Surface of specimens after triaxial testing

4.2 Stress–Strain Behavior and Peak Strength

The stress–strain curves attained on untreated and lime treated specimens prepared at 20 °C with different moisture contents and tested immediately after compaction are presented in Fig. 9. The data show that all untreated bentonite specimens exhibited ductile behaviour that was characterised by a gradual drop in the post-peak stress with increasing the axial strain. Following the treatment with 7% hydrated lime, the treated lime bentonite specimens behaved like a brittle material, exhibiting a rapid increase in the strength followed by a rapid drop in the post-peak stress with strain. Furthermore, it can be seen that the strain at failure for the natural clay is dramatically larger than that observed on the treated specimens, proving that the addition of lime alerted the properties of the clay from that of a ductile material to one of a brittle material. Failure was observed to occur at relatively small axial strains in the range of 1.0–3%.

Distinctive features for the effect of moisture content on the stress- relationships are pronounced on both the strength gain as well as the axial strain. For lime treated bentonite specimens at different moisture contents, the data showed that all treated specimens exhibited a clear strength peak that was observed at much lower strain between 1 and 2%. The data also showed that the gradient of the stress–strain relationship on treated specimens is several magnitudes higher than that recorded on untreated bentonite. Specimens prepared with a moisture content of 20% above the corresponding OMC experienced less strain at peak strength, which could be due to the effectiveness of chemical reactions in addition to the role of the suction head. Conversely, the lime treated bentonite specimens prepared with moisture content of 30% and 40% above the OMC value demonstrated an increased axial strain. The results suggested that the cementitious compounds were formed faster with increased moisture content resulting in a higher stress being sustained but due to the excessive availability of moisture in the pore voids the specimens experienced relatively large strain. Increasing moisture content more than 20% above the corresponding OMC did not show any favorable impacts on the strength gain. As failure and dilation of specimens primarily occur upon softening, this could be related to the breakage of cementation bonds (Mavroulidou et al. (2013).

Data for the stress–strain relationships on specimens of lime treated specimens with different bentonite content are presented in Fig. 9b. The data show that maximum value of strength was recorded on specimens with 85% clay content and moisture content of 20% above the corresponding OMC value. It is very clear that lime treated specimens irrespective of the bentonite content and moisture content are stiffer and more brittle than those which were untreated. The brittleness response for the treated specimens with 85% bentonite and moisture content of 20% above the corresponding OMC value could be attributed to the dominance of clay fraction over the sand fraction.

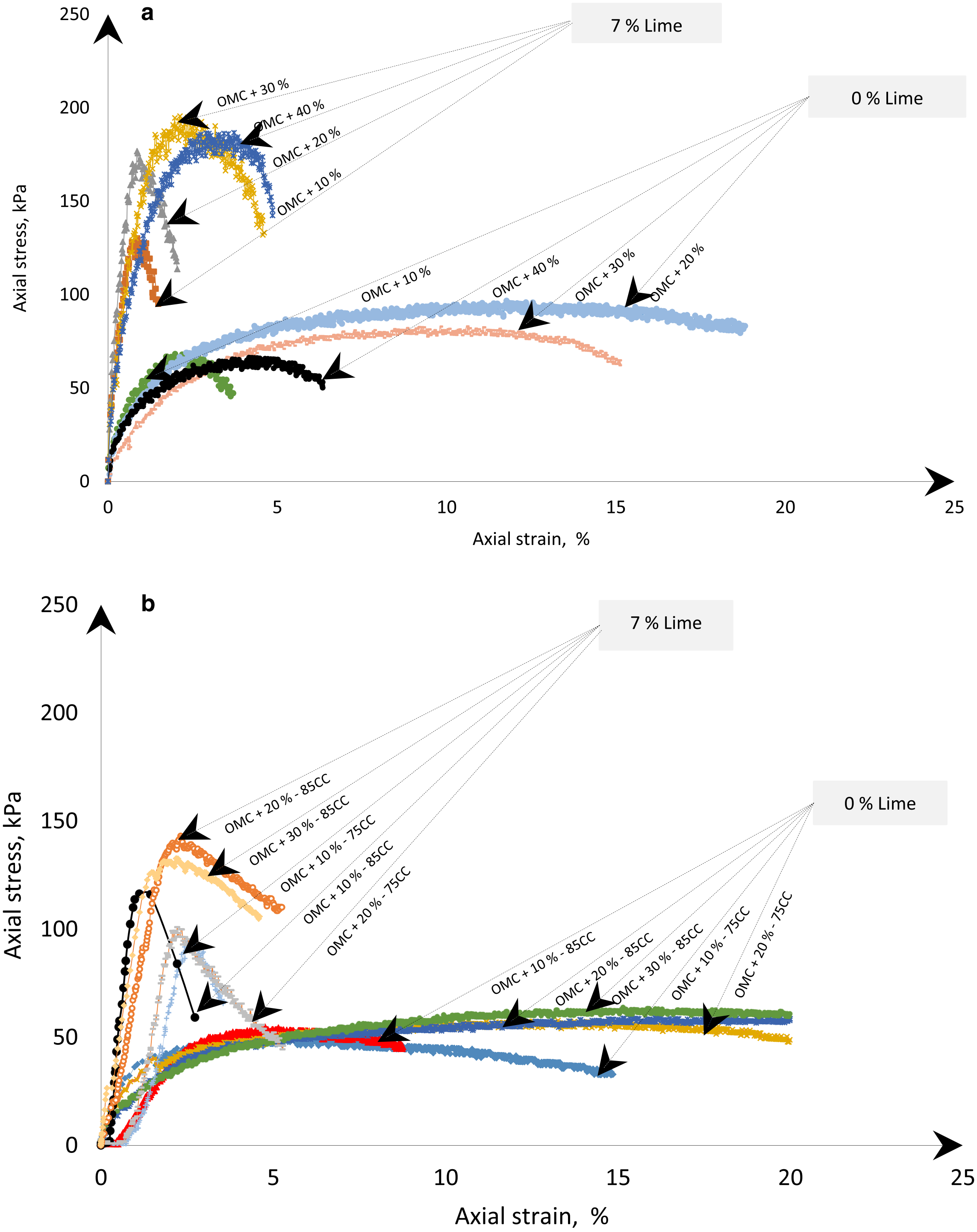


Fig. 9 Axial stress–strain behaviour of untreated and lime treated—a. clay and b. clay-sand mixtures at different water contents and tested immediately after compaction

Lower peak stresses on treated mixtures with 75% bentonite was observed due to the reduced bentonite content and enlarged void spaces with increased sand content as illustrated in Fig. 9. The brittleness is mainly due to the reorganization of clay particles by flocculation of aggregation and evolution of cementitious compounds on the bridges between clay particles and pore voids. However, the ductile behaviour is predominantly due to the dispersion of the clay particles and lubrication offered by the availability of water in the pore voids.

4.3 Impacts on California Bearing Ratio and Resilient Modulus

In road construction activities, the key parameters are California Bearing Ratio and Resilient Modulus. The two key parameters could be determined based on other measured soil characteristics. Kitazume and Satoh (2002) proposed Eq. 1 to determine the CBR from UCS data which was later used by Shahjahan (2010).

$$\mathrm{CBR}\ (\%\ ) = \frac{26.7}{\mathrm{UCS}} \tag{1}$$

Mr is a stiffness property obtained under repeated/cyclic load test (Mamatha and Dinesh 2017). As the laboratory determination of resilient modulus is costly and time consuming, Thompson and Robnett (1979) developed Eq. 2 to calculate the resilient modulus. Mokwa and Akin (2009) reviewed over thirty different correlations equations for the Resilient Modulus and sugeested that Thompson and Robnett's Eq. (1979) provided the best agreement to measured data.

$$\mathrm{M_r(MPa)} = 0.307 * \mathrm{UCS(kPa)} + 0.86 \tag{2}$$

Equations 1 and 2 show that CBR and M_r are directly dependent on the UCS value. Table 4 presents data for CBR results for treated clay specimens and shows that the addition of hydrated lime improved the CBR of the clay. These results are in harmony with those reported by Amadi and Okeiyi (2017). Apparently, lime treated specimens proved to be mechanically stronger which indicate a higher potential to sustain high bearing loads. The CBR values of the untreated clay at 20 °C were 2.6, 3.6, 3.1 and 2.5% for specimens prepared at 10, 20, 30 and 40% above the OMC respectively. When 7% lime was added to the clay, the CBR values after 672 h of curing increased to 12.8, 21.5, 27.6 and 25.40%. The improvement in the CBR is due to a gradual formation of cementitious materials associated with hydration of the lime and the pozzolanic reactions. Results to date demonstrated that the resilient modules of uncured lime-treated clay is substantially different from that of untreated clay (Robnett and Thompson 1976; Mamatha and Dinesh 2017). The resilient modulus values for different water contents at different curing periods were determined by Eq. 2. The resilient modulus values showed an increasing trend with increasing water contents up to 70%, suggesting that immediate exchange reactions have taken place. Similar trends were observed with increasing the curing time. For uncured lime treated clay, M_r values for specimens compacted at 10, 20, 30 and 40% above the OMC respectively after 28 days are 4.1, 5.1, 7.4 and 8.2 times higher than the untreated clay. However, the M_r values reduced at low water contents possibly due to non-availability of sufficient water to initiate the pozzolanic reactions. Table 5 shows the impacts of lime on the resilient modulus. Lime treatment increased the resilient moduli at moisture contents as high as 30

Table 4 Changes in CBR (%) values with water content and curing time

Curing time, h	Untreated clay	Treated clay		
	0	0	168	672
Water content, %				
50	2.6	4.9	11.4	12.8
60	3.6	6.6	17.6	21.5
70	3.1	7.3	21.3	27.6
80	2.5	7.0	20.9	25.4

Table 5 Changes in M_r (MPa) values with water content and curing time

Curing time, h	Untreated clay	Treated clay		
	0	0	168	672
Water content, %				
50	26.9	45.9	99.6	111.1
60	35.6	60.2	150.0	182.0
70	31.4	65.9	180.6	231.8
80	26.3	63.2	177.4	214.1

percent above the corresponding OMC. Bhuvaneshwari et al. (2019) stated that the higher moisture content accelerates the lime clay reactions which would have proceeded in a much slower rate as in low water contents. Thus, similar to the UCS results, CBR and M_r increased by adding lime and increasing the curing time.

4.4 Microstructural Analysis

To aid the discussion on evolution of strength and stress–strain relationships, SEM images have been taken and analysed with a key objective to highlight the salient features at micro-level. The SEM image of the untreated bentonite which is presented in Fig. 10 illustrates that the micro fabric of untreated bentonite is characterized by parallel arrangement of clay platelets which can be distinctly seen at magnification of 5000x. A dense matrix is observed with no aggregations of particle clusters.

Figures 11 and 12 present the microstructure of lime treated bentonite. Careful inspection of Figs. 10, 11 and 12 demonstrated significant differences between the microstructure of untreated and those of treated bentonite. Of note, SEM images were taken on specimens of 100% bentonite prepared with different moisture content as outlined in Table 3. Images of specimens prepared with moisture content of 10 and 20% above the corresponding OMC and cured at different temperature for different periods of curing are presented in Fig. 11a–f. The images show a considerable amount of voids in the structure within the aggregated stabilized bentonite clusters which is recognized by the dark background area of the photomicrographs. This means that although lime content was enough, sufficient water was not available for pozzolanic reactions to complete which resulted in a reduced strength to be recorded. This is supported by Liu et al. (2010) who stated that the moisture content required to achieve high strength fails to provide sufficient water to allow complete hydrolysis of the lime, this leads to lime deposition throughout the particles and because the cohesion or the friction angle of the lime is no appreciable, this results in reduction in the strength. Amaya et al. (2019) also attributed the reduction in strength to the low amount of water in the soil specimen, which is insufficient to hydrate all of the lime, which means that only a small amount of lime was hydrated, and the remainder remained in a free state. With the increase in the moisture content, sufficient cementing compounds are present within the specimens due to the pozzolanic reaction coating and joining the soil particles together making the voids in the soil to be less distinct, the particle stacking and aggregation with CSH materials can be observed in Fig. 12a–c. The particles of the clay became more oriented with increasing the moisture content, this increase led to a more homogeneous microstructure, more parallel particles and less voids.

The improvement in the mechanical properties of the bentonite with varying amount water was attributed to the aggregation microstructure of the clay particles. The calcium ions on specimens with moisture content of 30% above the corresponding OMC

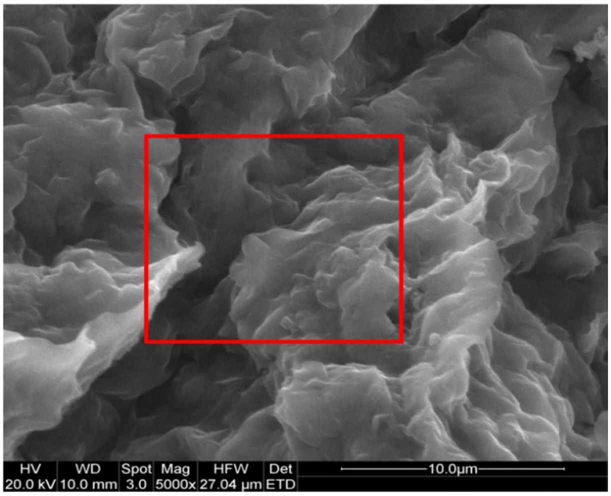
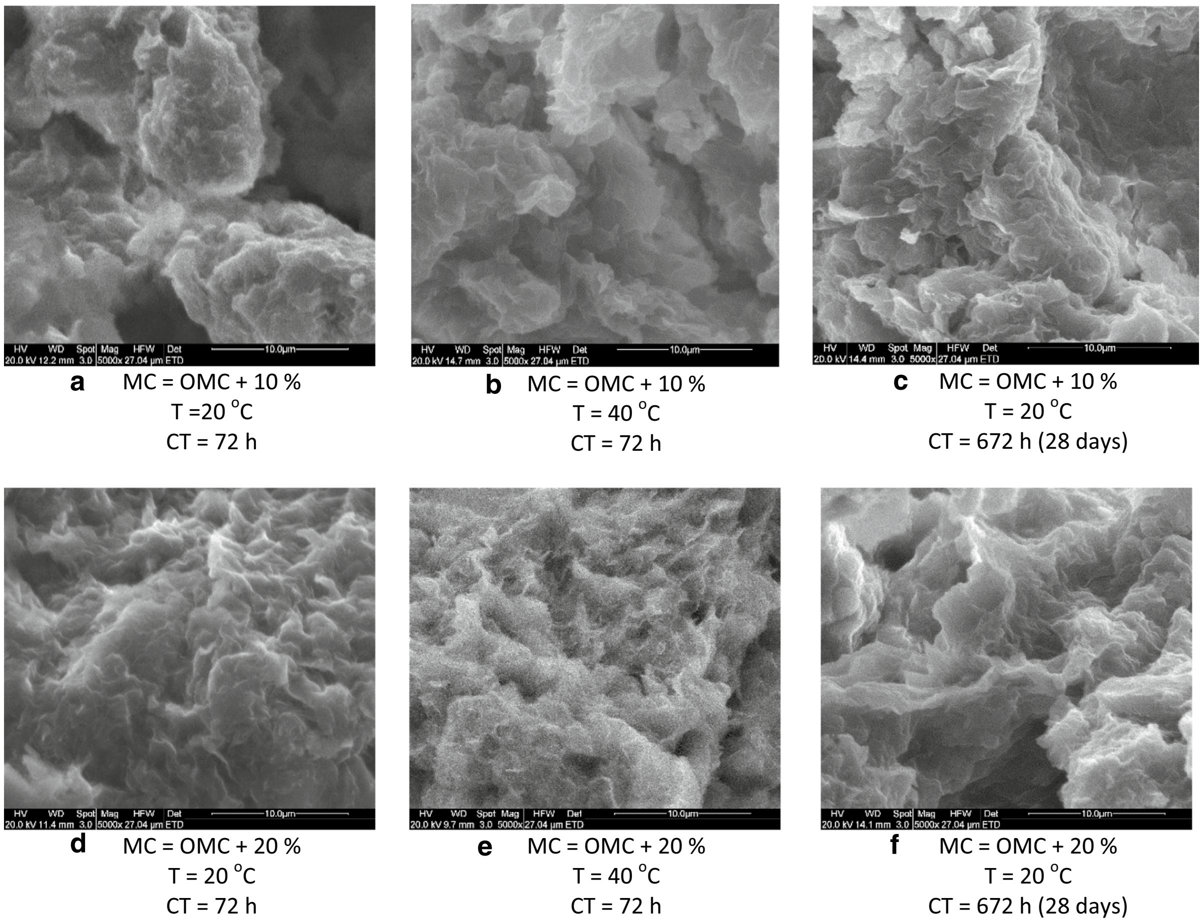


Fig. 10 SEM image of untreated bentonite specimen



a MC = OMC + 10 %
T =20 °C
CT = 72 h

b MC = OMC + 10 %
T = 40 °C
CT = 72 h

c MC = OMC + 10 %
T = 20 °C
CT = 672 h (28 days)

d MC = OMC + 20 %
T = 20 °C
CT = 72 h

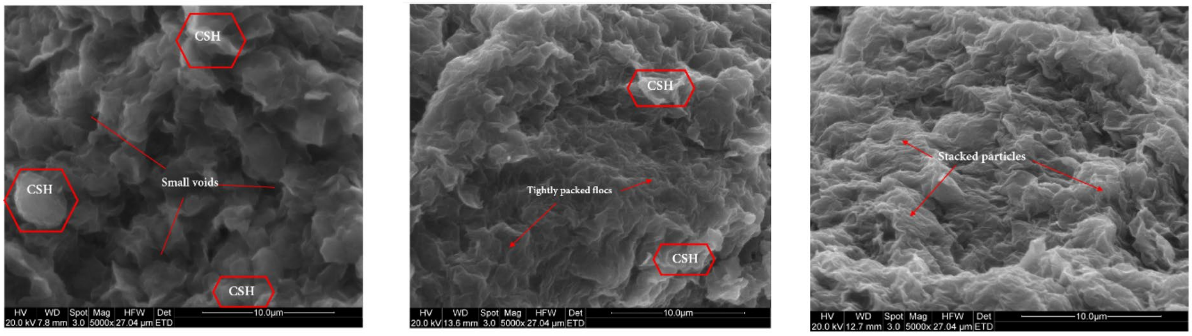
e MC = OMC + 20 %
T = 40 °C
CT = 72 h

f MC = OMC + 20 %
T = 20 °C
CT = 672 h (28 days)

Fig. 11 SEM images of lime-treated samples with moisture content of 10 and 20% above OMC

promotes linkage between the particles and as a result dense, tightly packed flocs are formed. These flocs behaved as individual coarse-grained materials. Bentonite became more packed and denser, clogging of fine particles and reorientation of particle resulted due to the water. It is clearly noticed that the SEM image of the stabilized specimen compacted with moisture content of 40% above the corresponding OMC and cured for 3 days at 20 °C has more pores than that compacted with moisture content of 30% above the corresponding OMC at the same curing conditions, Fig. 12d. The reason of decreasing the unconfined compressive strength with increasing the moisture content is associated with these pores which are not filled with cementing agents. The microstructural analysis corroborated the results of strength tests.

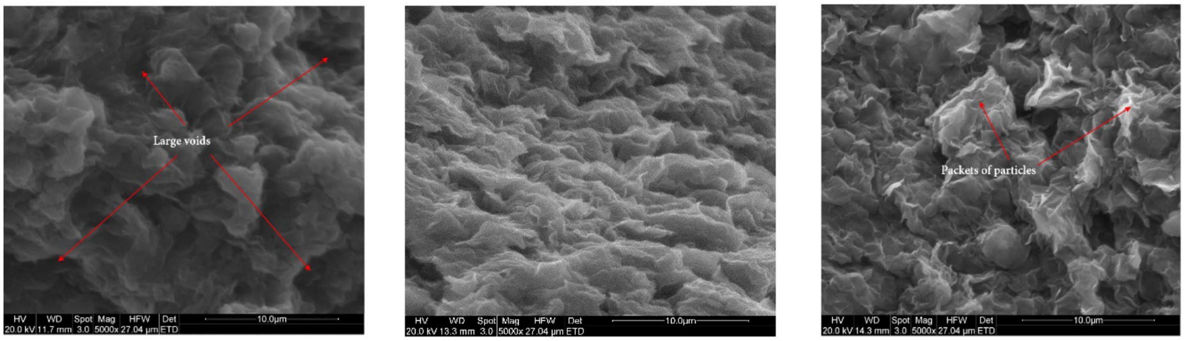
Regarding the role of curing temperature and time, the microstructure of 7% lime treated soil reveals the formation of clusters of clay particles, Fig. 12e–f. At OMC + 40%, with curing time, the large particles in the lime-clay sample are divided resulting in many packets of particles and forming a less compact structure than that observed when specimens were prepared with moisture content of 30% above the corresponding OMC value, see Fig. 12d. These results match those conducted by Ural (2016). An increase in temperature to 40 °C yielded a more flocculated structure in a short period of time of 3 days because of the accelerated chemical reactions and development of strength. It was noticed that the reactions involved in the samples compacted at the four water contents and cued at 40 °C for 72 h and those cured for 28 days at 20 °C showed similar behaviour. The



a OMC + 30 %
T= 20 °C
CT = 72 h

b OMC + 30 %
T = 40 °C
CT = 72 h

c OMC + 30 %
T = 20 °C
CT = 672 h (28 days)



d OMC + 40 %
T = 20 °C
CT = 72 h

e OMC + 40 %
T = 40 °C
CT = 72 h

f OMC + 40 %
T = 20 °C
CT = 672 h (28 days

Fig. 12 SEM images of lime-treated samples (OMC + 30% and OMC + 40%)

experimental results confirmed that a higher curing temperature gave rise to higher short-term strength. This was due to the pozzolanic reactions caused the particles to be packed increasing the bonding of particles in the specimen which in turn led to increasing the interlocking among particles. Thus, the microscopic assessment of the specimens was consistent with the observed strength and strain relations.

4.5 Failure Patterns

Assessment of the effect of moisture content on the failure mechanism has been carried out to identify common themes that occur on specimens with different clay content and as a result of curing time and temperature. Figure 13 presents images of the observed failure mechanism on clay specimens that were prepared with different moisture contents and cured at 20 °C. Inspection of Fig. 13 clearly demonstrated that the failure pattern was noticeably different and primarily dependent upon the moisture content of the specimens. Data recorded for the measured strain at failure illustrated that the strain gradually increased from 1.07% to 3.01% with increasing moisture content which was consistent with the observed failure pattern. Specimens prepared with moisture content of 10 and 20% above the corresponding OMC value experienced failure due to the occurrence of tensile cracks, bulging and non-uniform lateral dilation. It was clearly observable that the middle one-third of the specimen experienced most of the cracks and crushing by the top and bottom sections of the specimen. Whereas Specimens that were prepared with moisture content of 40% above the corresponding OMC value were failed by a cone-split at either the top or bottom end of the specimen. Translational

a OMC+10 % CT = 3 h

c OMC+20 % CT = 3 h

e OMC+30 % CT = 3 h

g OMC+40 % CT = 3 h

b OMC+10 % CT = 72 h

d OMC+20 % CT = 72 h

f OMC+30 % CT = 72 h

h OMC+40 % CT = 72 h

Fig. 13 Failure patterns of clay specimens

failure was recorded for specimens prepared with moisture of 30% above the corresponding OMC value which was dominated by a shear fault failure.

As visualized in Figs. 14a–d for failure approaches, the specimens bulged non-uniformly. Although the bonds seemed to be destroyed in specimens prepared with 75% bentonite content and cured for 3 h, the bonds can still exist in the wetter samples that cured for 72 h. The size of the cracks in specimens was thus seen to decrease with the increase in water content and bentonite content which could be attributed to the resilience and enhanced plasticity of specimens leading to withstanding a higher deformation. The higher degree of heterogeneity in the bentonite–sand specimens led to the attainment of lower strength values since failure occur through weakest zone in the specimen. Furthermore, during loading, sand particles and tiny sand-bentonite clusters were observed to fall

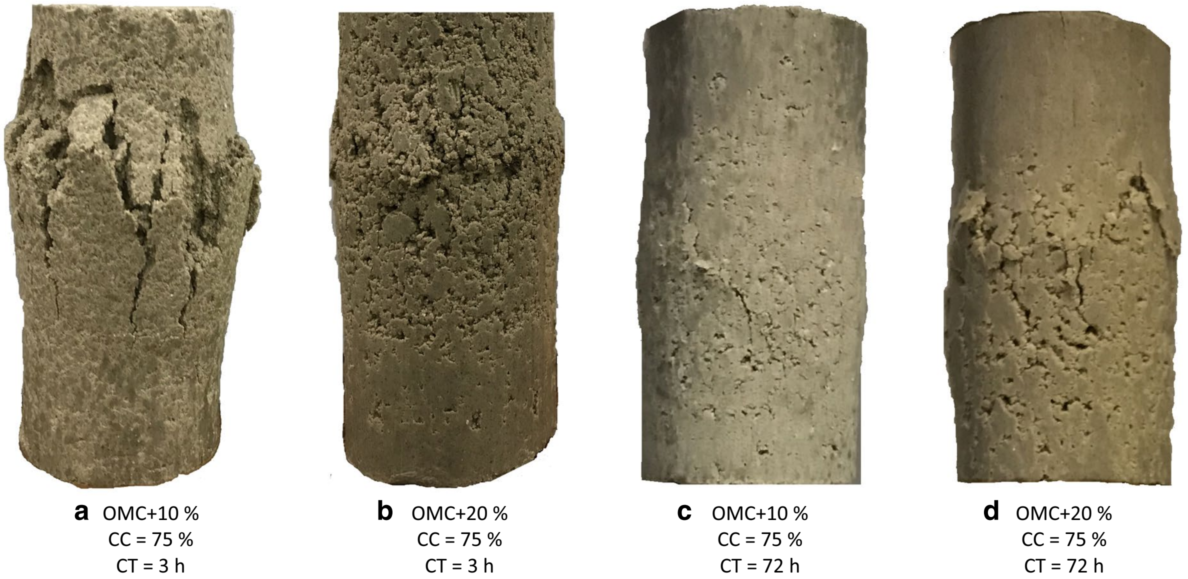


Fig. 14 Failure patterns of clay-sand specimens

from the sides of the specimens in particular on those which were prepared with lower moisture content e.g. 10% above the corresponding OMC value. This could be attributed to weak pozzolanic reactions leading to weaker bonding between the bentonite–sand clusters. As a result, a higher degree of variation in the cross sectional area was notable in the sand-bentonite specimens which would cause significant concertation in the stresses and failure which was similarity noted by (Khan et al. 2014)._ENREF_36 It should be noted that with decreasing the bentonite content by increasing sand content, relatively larger voids are formed which would reduce the forces exerted on the particles due to i. less matric suction head and ii. less bonding by the cementitious compounds. The microstructure of a soil is represented by the arrangement of the soil particles and how they are held together. The frictional contact between the particles resulting from external loads and the negative pressure in the curved moisture films bridging the soil particles and the internal bonds arising from cementing processes are the three main types of interactions between the particles (Hatibu and Hettiaratchi 1993). The behavior of the soil at failure was assessed which suggested that i. Brittle failure occurs if the specimen showed evidence of failure by brittle-columnar and faulting characteristics, ii. transitional, state between brittle and ductile failure, if the specimen failed by shear faulting and iii. ductile behaviour which is when observing ductile-faulting.

5 Economic Benefits of Lime Treatment and Recommendations

According to the experimental, addition of lime substantially increased the Unconfined Compressive Strength of the soil over time. In addition, the empirical results showed that when lime is added to soil, substantial improvements in CBR and M_r values are observed. The improvement of strength leads to short- and long-term economic benefits. Lime treatment represents a very economical means of improving the engineering properties of expansive soils. Based on Hopkins et al.'s study (2002), the costs of pavement sections built on treated subgrades are less than that built on untreated subgrades. Moreover, the pavement thickness resting on a stabilized subgrade can be thinner than that resting on un-stabilized subgrade. Kavak and Akyarlı (2007) stated that the use of lime treatment for road constructions decreases the thickness of the upper layers due to high CBR values and results in economic benefits to the overall construction. This is in agreement with Mamatha and Dinesh (2017)'s findings who found that the improved CBR due to lime treatment decreased the total pavement thickness by about 30%. NLA (2001) reported that, the short-term benefits, considering the structural contribution, lime-treated layers in pavement design creates cost-effective design alternatives. For example, Qubain et al. (2000) reported a saving of 25% on the budget when subgrade soils were treated by lime rather than replaced by by granular materials. Moreover, in the long-term, lime treatment provided performance benefits that decrease maintenance costs. Therefore, stabilizing a native clay subgrade with lime as part of an asphalt pavement project can reduce 30-year life cycle costs. It is essential that practitioners consider the way lime is mixed with native clays as well as the mixing water content in to order to achieve highest degree of improvement. The results clearly demonstrated that adding moderate amounts of water above the corresponding moisture content is beneficial which would accelerate the chemical reactions.

6 Conclusions

Three series of laboratory tests were carried out on lime treated highly reactive clays prepared at low unit weight to determine the effect of the moisture content. In addition, key parameters for road construction were determined based on empirical correlations. Based on the analysis of the findings from the present study, the following conclusions can be drawn out;

- The strength of lime- treated bentonite is significantly affected by the initial moisture content. The strength gain increased by up to 150% when the water content increased from 10 to 40% above the corresponding OMC value. Mixing more water is found favourable to speed up the chemical reactions and strength gain.
- The lime treated bentonite achieved its greatest strength gain when the specimens were prepared with moisture content of 30% above the OMC value and cured at 20 °C. However, when specimens were cured at 40 °C, highest strength was recorded on specimens with moisture content of 40% above the OMC value.
- The attained strength gain on specimens with different bentonite content clearly demonstrated the significant effect of bentonite content. Specimens with reduced bentonite content experienced less strength which could be attribute to reduction on the amount of cementitious compounds, less absorption of water by sand particles, bigger pore voids and less matric suction head.
- The results indicated that California Bearing Ratio and Resilient Modulus values are directly reliant on the UCS value. Thus, similarly significant improvement can be achieved by the addition of lime and increasing the curing time.
- It is recommended that in the practice of lime stabilisation, the expansive clay should be compacted at a moisture content that is moderately higher than the optimum moisture content.
- Increasing moisture content between 20 ~ 40% above the corresponding OMC was found to cause a considerable increase in the observed strain although the max strength was slightly affected.
- The observed failure pattern was also found to be affected by the moisture content. Bulging, shear and cone-spilt are the three patterns observed in this study which occur with the increase in moisture content above the OMC value.
- The fabric of lime treated bentonite shown by the SEM-micrographs indicated the formation of cementitious compounds. These compounds resulted from the pozzolanic reactions contributed to the increase in the strength of the treated clay. Specimens prepared with moisture content of 30% above the OMC value illustrated that the microstructure was characterized by an assembly of clay particles. Bentonite became more packed and denser, clogging of fine particles and reorientation of particle resulted due to the water leading to a homogeneous microstructure.

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Declarations

Conflict of interest The authors have not disclosed any conflict of interest.

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