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Strength improvement of lime-treated clay with sodium chloride

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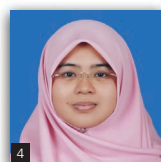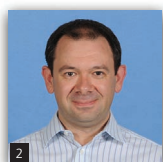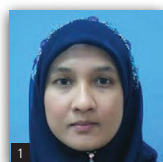
Lime stabilisation of organic clay has often been studied in the past. However, there is some evidence in the literature
that the presence of high concentrations of organic matter in clay soil can lessen the chemical reaction between lime
and clay minerals and can have detrimental effects on the engineering properties of soil. Hence, in this paper, the
stress–strain behaviour and strength properties of organic soil treated with lime and sodium chloride (NaCl) are
analysed. A soil mixture, prepared with 5% lime content and 1·5% humic acid, was stabilised with varying quantities
of sodium chloride (0·5, 2·0 and 5·0%). Consolidated undrained and drained triaxial tests were carried out on
specimens at curing periods of 7 and 28 d with applied confining pressures of 50 and 100 kPa. Scanning electron
microscopy and X-ray diffraction analysis were used to observe the microstructural changes resulting from cementation
materials. It was found that the introduction of sodium chloride improved considerably the strength properties of the
lime-treated organic clay. The microstructural analysis also confirmed the presence of calcium silicate hydrate in a salt-
treated organic clay, which was the main contributing factor to the enhanced engineering properties of the clay.

Notation

a	q value that intercepts at y-axis from q–p' space
C_c	compression index
c'	effective cohesion: kPa
e_i	initial void ratio
m	gradient of slope/$(q/p')_p$
O_{MC}	optimum moisture content
O_{SC}	optimum salt content
p'_c	pre-consolidation pressure
p'_o	overconsolidation ratio
q_p	peak deviator stress: kPa
$(q/p')_p$	peak effective stress ratio
w_i	initial water content
Δu	excess pore water pressure: kPa
ε_a	axial strain
ε_v	volumetric strain
σ_1	major principal stress
σ_3	minor principal stress
σ'_3	effective confining pressure: kPa
ϕ'	effective friction angle: °

Introduction

There is some evidence in the literature that the occurrence of
high concentrations of organic matter, in particular humic acid, in

clay soil can weaken the chemical reaction between lime and clay
minerals and can have negative effects on the engineering
properties of the soil (Chen *et al*., 2009; Hebib and Farrell, 2003;
Kang *et al*., 2017; Koslanant *et al*., 2006; Onitsuka *et al*., 2003;
Petry and Glazier, 2004). Sakr and Shahin (2009) demonstrated
that soft clay with a high organic content of 14% can be
successfully stabilised with 7% lime. However, according to Petry
and Glazier (2004), the presence of more than 4% organic matter
reduces the compressive strength of lime-stabilised weathered
clay. This suggests that some organic compounds do not have a
detrimental effect on the cementing reaction. It was reported that
although the lime-treated specimens of organic clay exhibited
significant strength gained compared to that of the untreated
specimens, the probabilities of long-term strength development in
the specimens were still indeterminate. This happens because
humic acid disturbs the pozzolanic reaction process that occurs
between lime and clay by obstructing or slowing it down. It also
results in a decrease in the pH of the mixtures' pore solution.

A highly alkaline environment (if allowed) elongates the duration
required for the dissolution of alumina and silica. Therefore, the use
of only lime may not be sufficient or effective in stabilising organic
soils. Adding a considerable quantity of lime to the soil is an
effective way to moderate the unfavourable effects of humic acid. It

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is deemed that addition of lime could neutralise humic acid if an adequate amount of binder is also added. However, this method is not cost-efficient. Another method that could neutralise humic acid is the addition of selected salts, which play the role of additional binders to help lime react during the stabilisation process of organic clay. It has been observed that humic acid coats the clay particles and thereby behaves as a barrier to lime and clay (Abood et al., 2007; Ahnberg, 2004; Koslanant et al., 2006; Kuno et al., 1989). The addition of salts to the organic clay coagulates the soil, thereby causing the clay particles to expose themselves to the lime for pozzolanic reactions.

Previously, it was found that more than 1% humic acid content in clay may render the lime stabilisation process ineffective (Harris et al., 2009; Huat et al., 2005; Koslanant et al., 2006; Zhu et al., 2009). More recently, it has been reported that there is a significant loss of strength in lime-treated organic clay that has a humic acid composition equal to or greater than 1·5% (Mohd Yunus et al., 2013a; Mokhtar and Swamy, 2010). Hence, it is important to consider the possible advantages of using additives or additional binders for enhancing the lime stabilisation process in organic clays with a noticeable humic acid content. It was reported in the literature that salt additives, such as sodium chloride (NaCl), can be used as an admixture so that the characteristics of the lime-treated organic clay can be improved (Asghari et al., 2003; Davoudi and Kabir, 2011; Marks and Haliburton, 1999; Modmoltin and Voottipruex, 2009; Murty and Krishna, 2007; Onitsuka et al., 2002, 2003; Ramana and Hari Krishna, 2006; Ramesh et al., 1999; Sharma et al., 2008; Stipho, 1989). The salt additives, being more readily soluble in water than lime, provide the required cations that are necessary for cation exchange. Moreover, excess sodium ions (Na^+) stimulate an increased production of pozzolanic compounds and are regarded as advantageous to the soil's silica dissolution. Moreover, the presence of sodium ions in solution is believed to compress a diffuse water layer, thereby increasing interparticle contact and aiding the flocculation process, which lead to formation of cementing materials due to chemical reactions (Davoudi and Kabir, 2011; Marks and Haliburton, 1999).

So far, there has been no evidential academic discourse on the impact of salts on the stress–strain behaviour of lime-treated organic soil using triaxial compression testing. Hence, an experimental study on the behaviour of lime-treated organic clay based on consolidated undrained (CU) and consolidated drained (CD) triaxial tests with various sodium chloride contents (0·5, 2·0 and 5·0%) and at curing periods of 7 and 28 d was carried out to consider the possible advantages of using additives or additional binders for enhancing the lime stabilisation process. A microstructural analysis (scanning electron microscopy (SEM) and X-ray diffraction (XRD)) was conducted to offer further insights and clarify the engineering test results on the particle level.

Materials and specimen preparation

The artificial organic clay used in this study was prepared by mixing a commercial kaolin with 1·5% commercial humic acid according to

the dry mass of kaolin. Humic acid is a well-known constituent of organic matter with the potential to disrupt the soil stabilisation process (Petry and Glazier, 2004). A mixture of 1·5% humic acid, at 5% optimum lime content, was prepared to be stabilised with various amounts of sodium chloride (Chen et al., 2009; Mohd Yunus et al., 2013a; Petry and Glazier, 2004). The salt was added to the lime-treated organic clay in the amounts of 0·5, 2·0 and 5·0%. The results of index testing carried out on untreated specimens are summarised in Table 1. More details on the physical properties of the untreated organic clay can be found in the paper by Mohd Yunus et al. (2012).

The specimens tested in this study were prepared using the standard procedures described in ASTM D 5102-96 (ASTM, 2004). Initially, the specimens were oven-dried at 60°C until a constant weight was obtained. Untreated organic clay was prepared by mixing dry kaolin with 1·5% humic acid by dry mass of kaolin. Then, 5% of lime content and different amounts of sodium chloride were added to the predetermined amount of organic clay. Mixing of dry materials was continued until a uniform appearance of the soil mixture was obtained. Distilled water was then added according to the optimum moisture content (O_{MC}) of untreated organic clay, determined using the standard Proctor test (Mohd Yunus et al., 2012), and further mixing was performed until a homogeneous appearance of the soil paste was achieved. In this study, all of the specimens were compacted at similar densities and water contents as specified in Table 1 to perform comparable analysis.

The process of mixing was conducted as quickly as possible to ensure that lime was not exposed to air for too long. This was necessary to avoid the carbonation process that could affect the strength characteristics of lime-treated specimens. The specimens were compacted into the mould (76 mm high and 38 mm in diameter) at a specified moisture content to achieve the specified dry density. A small amount of grease was applied inside the brass mould to minimise friction. The specimens were then extruded from the mould and wrapped in cling film to preserve the water content and to keep them free from carbon dioxide (CO_2). The specimens were then cured in desiccators at 20°C and with humidity more than 90% for 7 and 28 d. A back pressure of 400 kPa was applied to all the samples to ensure saturation of the soil. A specimen was regarded as sufficiently saturated when Skempton's B value was greater than 0·95 for untreated soil and 0·90 for treated soil.

Table 1. Physical properties of clay with 1·5% humic acid content

Property	K1·5HA
Liquid limit: %	63·6
Plastic limit: %	33·8
Plasticity index: %	29·5
Specific gravity	2·61
pH	5·16
O_{MC}: %	30·6
M_{DD}: kg/m³	1425

K, kaolin; HA, humic acid; O_{MC}, optimum moisture content; M_{DD}, maximum dry density

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Results and discussion

The results of the CU and CD triaxial tests carried out on the stabilised clay specimens are presented in this paper based on a stress path analysis representing the successive states of stress during the shearing stage. The triaxial tests were conducted following 7 and 28 d of curing and were based on BS 1377-8:1990 (BSI, 1990). Effective confining pressures (σ_3') of 50 and 100 kPa were applied, respectively.

Undrained behaviour

The changes in the stress–strain behaviour of lime-treated organic clay due to the influence of sodium chloride content after 7 d of curing are presented in Figure 1. To begin with, an effective confining pressure (σ_3') of 50 kPa was applied. As shown in
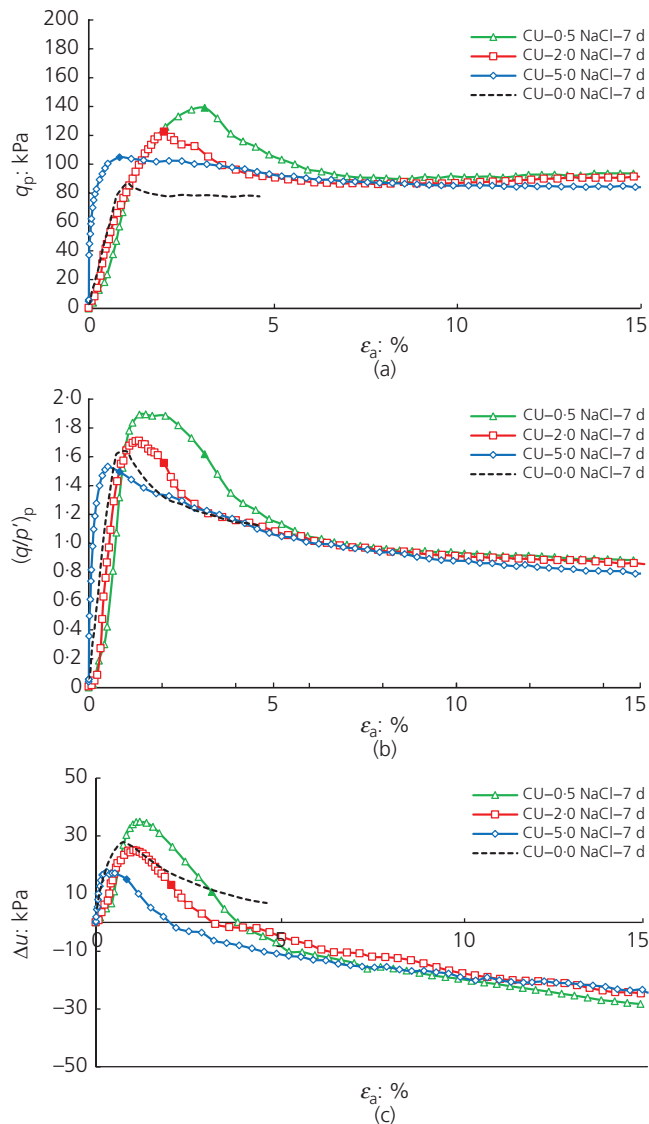
Figure 1. Effects of sodium chloride content on the undrained behaviour of lime-treated organic clay at 7 d of curing: (a) q_p–ε_a, (b) $(q/p')_p$–ε_a and (c) Δu–ε_a

Figure 1(a), it is observed that specimen failures occur at the peak deviator stresses (q_p) that correspond to relatively small axial strains in the range of 0·5–3·5%. The specimen's failure in all the tests conducted was associated with shear band formation, which was in agreement with the tests carried out by Hebib and Farrell (2003) and Koslanant et al. (2006).

Figure 1(a) shows that, except for the lime-treated organic clay that contains 0·5% sodium chloride, a gradual decline in the deviator stress with increased strain is observed in the q_p values of all other specimens, until there is no further substantial change in the stress. These types of soils that demonstrate such behaviour at the maximum stress are considered to have endured strain softening.

It can be observed from Figure 1(a) that there is a decrease in the peak deviator stress (q_p) of specimens with an increase in the sodium chloride content. More precisely, there was a reduction in q_p from 139 kPa (0·5% sodium chloride) to 123 and 105 kPa for 2·0 and 5·0% sodium chloride, respectively, which indicates that 0·5% sodium chloride is considered as the optimum salt content (O_{SC}) to be stabilised with lime-treated soil. Despite observing a decrease in q_p at higher salt content, the q_p of each specimen treated with salt was still higher than the q_p of the specimens treated with only lime (depicted with black dashed lines in all the figures). It needs to be noted that the specimen without any salt contains 1·5% humic acid and is treated with 5% lime. Figure 1(a) shows that the q_p of the specimen with the lowest salt content (0·5% sodium chloride) was almost twice as large as the q_p of the specimen that had 0% salt content. The q_p value of lime-treated organic clay with 0·5% sodium chloride was 139·1 kPa, while the q_p of lime-treated organic clay without salt was only 86·6 kPa.

Figure 1(b) shows the influence of salt content on the peak effective stress ratio $(q/p')_p$ for specimens stabilised with sodium chloride, The CU test results indicate that the peak $(q/p')_p$ did not occur simultaneously with the q_p. The $(q/p')_p$ was reached marginally earlier than the q_p, at about 0·5–1·5% axial strain. Differences in the positions of $(q/p')_p$ and q_p were observed as a result of the variations in pore water pressure during shearing under undrained conditions (Figure 1(c)) and because q_p is not a function of pore water pressure. Figure 1(c) shows that $(q/p')_p$ was reached at the same strains as the peaks of Δu. Figure 1(c) also illustrates the variations in excess pore water pressure (Δu) during the course of undrained shearing for specimens with different levels of sodium chloride content. The rise in negative Δu in specimens that were treated with decreasing salt content goes on to prove that an increase in the effective stress is consistent with the plots of q_p and $(q/p')_p$ against ε_a. It is thought that salt content exceeding 0·5% may provide surplus cations, which in turn create an unbalance in the exchange activity of cations (Davoudi and Kabir, 2011; Kazemian et al., 2011). Subsequently, this deters the flocculation process that takes place in the early phases of stabilisation. On the whole, the results derived from the CU triaxial tests demonstrate the efficacy of salt addition in increasing the strength of lime-treated specimens in just 7 d of curing.

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The behaviour of lime-treated organic clay that contains different amounts of sodium chloride after 28 d of curing is presented in Figure 2. Figure 2(a) shows that the q_p–ε_a curves of the lime-treated specimens with the addition of chloride salt were considerably different from those of the specimens without any salt (shown with a black dashed line). Despite a noticeable reduction in the deviator stress after longer curing periods of the lime-treated organic clay (Mohd Yunus et al., 2012, 2013a, 2013b, 2014; Thangavel et al., 2010), the addition of salt resulted in considerable improvement of the specimens. The observation made after 7 d of curing showed a similar outcome, where q_p increased as the salt content decreased. This indicates that with the addition of small amounts of salt, it is feasible to attain effective stabilisation of lime-treated clay specimens that have 1·5% humic acid content. Compared to the q_p of specimens with 0% salt content, the q_p of specimens with salt are three to four

times higher. For example, the q_p of lime-treated organic clay with 0·5% sodium chloride was 210·3 kPa, while the q_p of the lime-treated organic clay without salt was only 47·6 kPa. It is hypothesised that the improvement in clay behaviour due to the addition of the salt was achieved because of the initial effect of 5% lime content that stimulated the dispersion of calcium (Ca^{2+}) ions, which in turn had an important role to play in the flocculation and pozzolanic reaction processes. Moreover, the addition of 0·5% sodium chloride resulted in supplementary contact that helped in modifying the chemical reaction between sodium ions and clay minerals. Although at this phase, the impact of various curing periods has not been evaluated, the current observations validate the benefits of adding salt to the lime-treated organic clay in the long term.

Figure 2(b) shows that similar to the q_p–ε_a curves, the $(q/p')_p$ values of the lime-treated organic clay, with different levels of sodium chloride content, increase after 28 d of curing as the salt content decreases. Also, it has to be mentioned that $(q/p')_p$ attained its maximum value a little before the peak deviator stress. Moreover, as shown in Figure 2(c), the negative Δu increased as the salt content decreased, which in turn implies increase in the effective stresses.
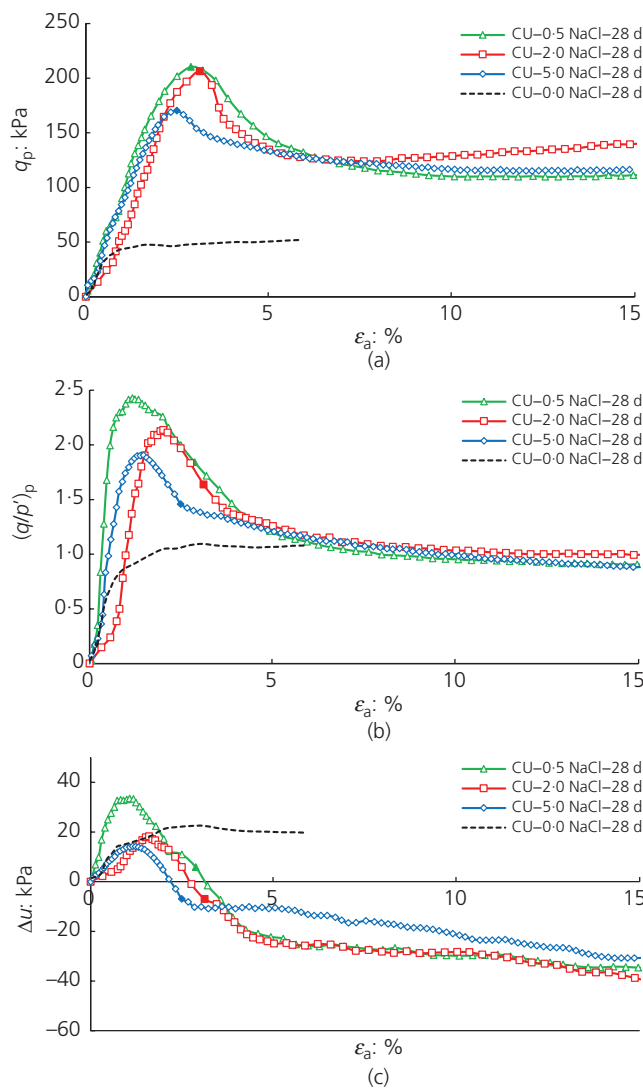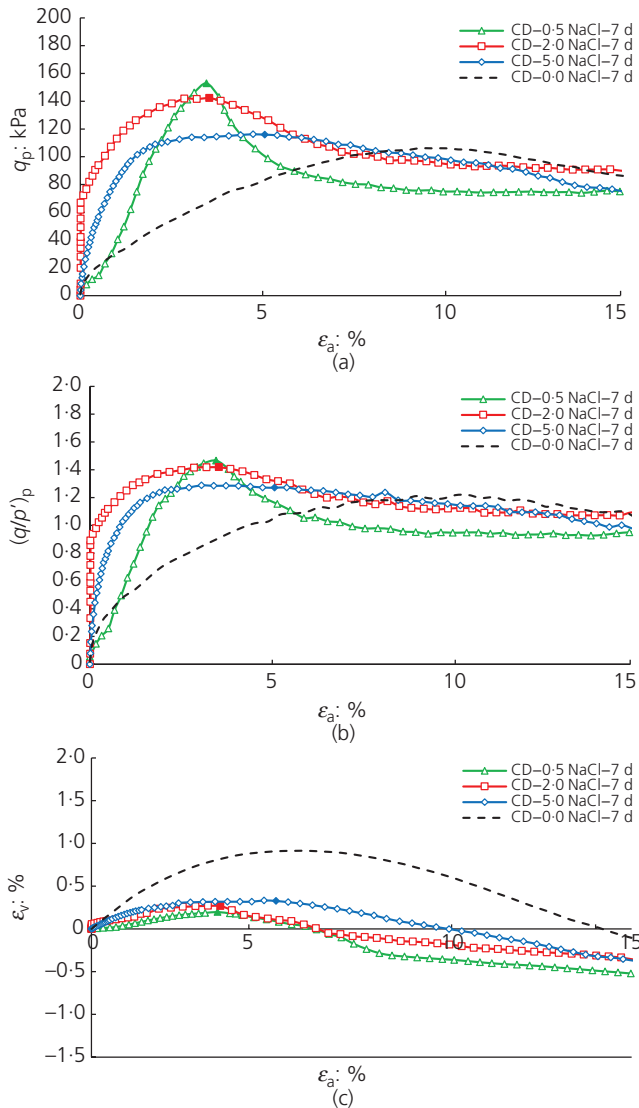
Drained behaviour

The stress–strain behaviours of the lime-treated organic clay specimens with a range of sodium chloride contents and sheared under drained environments were tested immediately after 7 and 28 d of curing to make sure that there is valid comparability with the CU tests. Figure 3 presents the impact of adding varying amounts of sodium chloride to lime-treated clay with 1·5% humic acid content after 7 d of curing. Moreover, the improvement in the properties of the clay attained by adding chloride salt was compared with the results of the tests carried out on the specimens treated with lime alone, and the outcomes are illustrated with dashed lines. It was observed that the failure of specimens occurred at the peak deviator stress (q_p). Figure 3(a) shows that the q_p for the specimens with salt was attained at axial strains in the range of 1·5–5·0%. The q_p in the CD tests, similar to that in the CU tests, decreased as the salt content increased. The q_p decreased from 153 to 142 kPa (for 0·5% sodium chloride) and 116 kPa (for 2·0 and 5·0% sodium chloride). Also, it was noticed that the q_p for all the specimens treated with chloride salt was higher than that of the specimens treated with 5% lime alone (that is, q_p = 106 kPa). This implies that the addition of salt effectively altered the characteristics of the lime-treated clay that contains 1·5% humic acid. Figure 3(b) shows the impact of sodium chloride on the effective stress ratio $(q/p')_p$. The results of the CD test indicate that $(q/p')_p$ is attained at the same ε_a as the q_p. Figure 3(c) presents the variation in volumetric strain (ε_v) with axial strain (ε_a) for lime-treated specimens with sodium chloride content after 7 d of curing. Compared to the specimens with 0% sodium chloride, the specimens with chloride salt demonstrated an increase in the dilative behaviour at large axial strain, with an increase in the magnitude of dilation, as the salt content decreased.
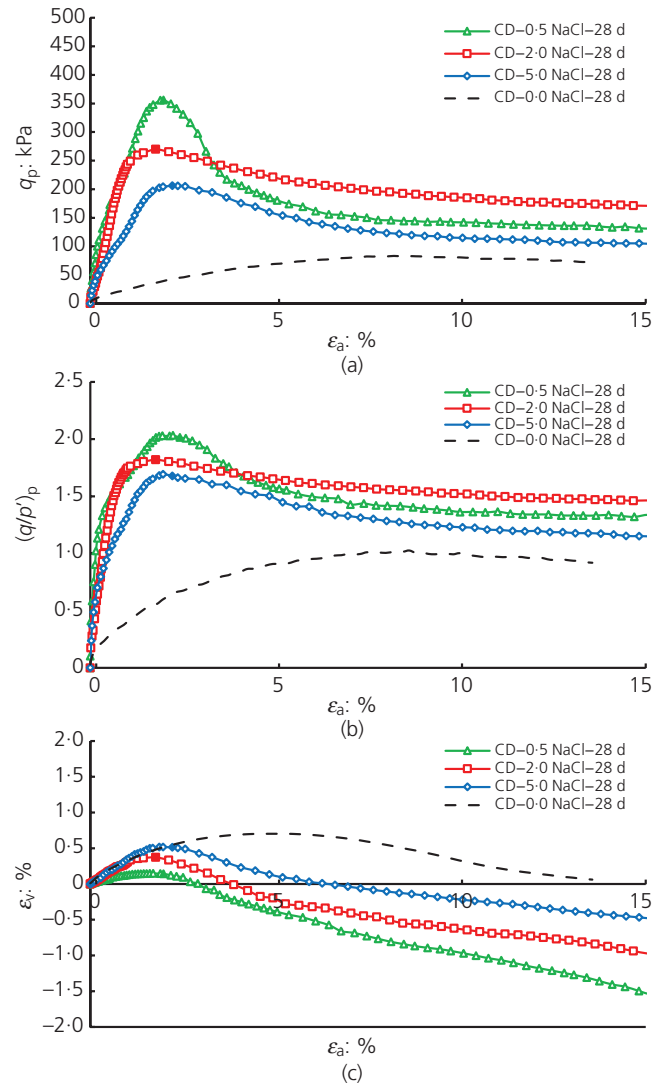
It is necessary to note at this stage that the dilative behaviour has a substantial positive impact on the shear strength of the soil (e.g.

Figure 2. Effects of sodium chloride content on the undrained behaviour of lime-treated organic clay at 28 d of curing: (a) q_p–ε_a, (b) $(q/p')_p$–ε_a and (c) Δu–ε_a

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Figure 3. Effects of sodium chloride content on the drained behaviour of lime-treated organic clay at 7 d of curing: (a) q_p–ε_a, (b) $(q/p')_p$–ε_a and (c) ε_v–ε_a

Figure 4. Effects of sodium chloride content on the drained behaviour of lime-treated organic clay at 28 d of curing: (a) q_p–ε_a, (b) $(q/p')_p$–ε_a and (c) ε_v–ε_a

Chu *et al.*, 2015; Lade and Trads, 2014; Likitlersuang *et al.*, 2014). This suggests that the tendency of lime-treated specimens containing salt to exhibit a dilative behaviour during drained loading results in an increase in the soil's shear strength within 7 d of curing.

Figure 4 illustrates the impact of sodium chloride on the stress–strain behaviour of lime-treated clay with 1·5% humic acid after 28 d of curing. It is evident from Figure 4(a) that the q_p values of all specimens that contain chloride salt were significantly higher than those of the specimens without salt. According to the test results, there was a considerable increase in strength, between 147 and 450%, from the q_p value of the specimen without salt, which was only 83 kPa. The specimens with 0·5% sodium chloride

exhibited the highest q_p, corresponding to 356 kPa. The behaviour resembled the observation after 7 d of curing (Figure 1(a)), and in this case as well, the q_p was noted to decrease as the salt content increased. Figure 4(b) illustrates the influence of salt content on the peak effective stress ratio $(q/p')_p$ after 28 d of curing. It can be concluded from the test results that the $(q/p')_p$ values of specimens with salt were much higher than those of the specimens without any salt. There is a consistent relationship between a high $(q/p')_p$ and a low level of chloride salt. Figure 4(c) presents the change in the volumetric strains (ε_v) of specimens with chloride salt measured at 28 d of curing. It has been observed that for specimens containing chloride salt, the amount of dilation increases as the salt content decreases. As mentioned earlier, the dilative behaviour of soil is linked with high shear strength. Therefore, it can be concluded that the specimens with low salt content (0·5% sodium

chloride) are characterised by a higher shear strength. This is discussed in detail in the next section.

Comparison between CU and CD triaxial tests

Figure 5 presents the effective stress paths of lime-treated organic clay containing 0·5% sodium chloride. A comparison was made between the effective failure parameters calculated from the CU and CD tests. The peak effective stress states, derived from each effective stress path, were connected to determine the resulting failure lines. Figure 5 shows the impact of adding 0·5% sodium chloride on the q–p' plot that was assessed based on the specimens without lime content. Figure 5 shows that the stress paths of the CU samples led to the same failure envelopes as that of the CD samples. This outcome reveals that the failure parameters derived from the CU and CD tests were consistent. Moreover, the equations given in Figure 5 show that the slopes of failure line determined for the specimens containing chloride salt were steeper than those without any salt content.

The effective shear strength parameters (c' and ϕ'_p) were also determined for the lime-treated specimens containing 0·5% sodium chloride. With the help of Equations 1 and 2, the values for c' and ϕ'_p were calculated.

1. $\phi'_p = \sin^{-1}[3m/(6 + m)]$

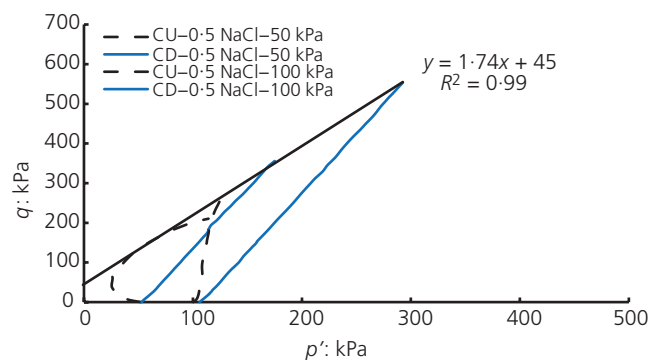2. $c' = (a \tan \phi')/m$

where m is the gradient of slope/$(q/p')_p$; ϕ' is the effective friction angle; q is the deviator stress ($\sigma_1 - \sigma_3$); p' is the mean effective stress ($1/3\ (\sigma_1 + 2\sigma_3)$); a is the intercept at y-axis; σ_1 is the major principal stress; and σ_3 is the minor principal stress.

For samples containing 0·5% sodium chloride, the calculated c' value was equal to 23·6 kPa. This value is significantly higher than the value for the samples without any salt (0% sodium chloride), where c' was about 7·1 kPa. Moreover, the ϕ'_p of the lime-treated specimen with 1·5% humic acid increased substantially from 20·7° for 0% sodium chloride to 42·4° for 0·5% sodium chloride. The increased values of c' and ϕ'_p confirm that the effective shear strength of organic clay can be successfully improved by the addition of a small amount of sodium chloride, which in this particular case is 0·5%. Furthermore, the triaxial test results clearly show that the shear strengths of lime-treated clay specimens, containing 1·5% humic acid, increase on addition of 0·5% sodium chloride.

In addition to the strength tests, the compressibility behaviour of lime-treated organic clay with varying amounts of sodium chloride was studied at 7 d of curing. As with the strength tests, all of the specimens were prepared with 1·5% humic acid and 5% lime content. Furthermore, each specimen had an initial water content of 63%, corresponding to the liquid limit of lime-treated clay containing 1·5% humic acid. Tables 2 and 3 provide the initial properties of the lime-treated organic clay without and with addition of sodium chloride, after 7 and 28 d of curing, respectively. Table 2 also shows initial void ratios (e_i) of specimens varying from 1·47 to 1·58. The variation in e_i is due to the changes in water content. It can be seen from Table 2 that the initial water contents of the cured specimens to which the chloride salt had been added were noticeably lower than those without salt. The difference in the water content is observed due to a more effective hydration process that had occurred during curing after salt was introduced. Similar observations were reported by Chen and Wang (2006).

Figure 6 shows the compression curves of lime-treated specimens containing sodium chloride after 7 d of curing. It shows the impact

Figure 5. Stress paths and failure envelope of organic clay treated with 5% lime and 0·5% sodium chloride

Table 2. Summary of oedometer test results on lime-treated organic clay with varying amounts of sodium chloride after 7 d of curing

|	Specimen			
	0% Sodium chloride	0·5% Sodium chloride	2·0% Sodium chloride	5·0% Sodium chloride
Diameter: mm	75	75	75	75
Height: mm	19·2	19·2	19·2	19·2
Initial water content w_i: %	62·9	58·6	59·4	60·2
Initial void ratio e_i	1·58	1·47	1·49	1·51
Compression index C_c	0·33	0·24	0·31	0·37
Pre-consolidation stress p'_c: kPa	115	125	120	80
Overconsolidation ratio ($p'_o = 50$ kPa)	2·3	2·5	2·4	1·6
Overconsolidation ratio ($p'_o = 100$ kPa)	1·15	1·25	1·2	0·8

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Table 3. Summary of oedometer test results on lime-treated organic clay with varying amounts of sodium chloride after 28 d of curing

	Specimen			
	0% Sodium chloride	0·5% Sodium chloride	2·0% Sodium chloride	5·0% Sodium chloride
Diameter: mm	75	75	75	75
Height: mm	19·2	19·2	19·2	19·2
Initial water content w_i: %	60·6	56·6	57	58·2
Initial void ratio e_i	1·52	1·42	1·43	1·46
Compression index C_c	0·34	0·22	0·26	0·31
Pre-consolidation stress p'_c: kPa	80	140	130	121
Overconsolidation ratio ($p'_o = 50$ kPa)	1·6	2·8	2·6	2·42
Overconsolidation ratio ($p'_o = 100$ kPa)	0·8	1·4	1·3	1·21

that different amounts of sodium chloride have on the void ratios of the lime-treated specimens. It can be seen that the ε_v of the specimens with 0·5 and 2·0% sodium chloride decreases much less compared to the ε_v of the specimens without salt. However, Figure 6 shows that the lime-treated specimens with 5% sodium chloride have undergone significantly more compression than those without salt despite having reduced void ratios at the beginning of compression. Such behaviour indicates that the properties of salt-treated specimens after 7 d of curing improved with the addition of up to 2% sodium chloride. Further addition of sodium chloride does not improve the compression behaviour of lime-treated clay.

The compression results are also consistent with the strength tests where the optimum salt content ($O_{SC} = 0\cdot5\%$) was determined. Any further addition of chloride salt beyond $O_{SC} = 0\cdot5\%$ did not contribute towards improving the strength properties of lime-treated organic clay. The earlier-mentioned reduction in the void ratio and the consequent improvement in the soil structure support the results of previously reported triaxial tests conducted on similar specimens cured for the same period of time. Therefore, the results obtained from both types of tests suggest that the reduction in the void ratio of the salt-treated specimens was caused by the formation of cementitious products (i.e. calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH)), which subsequently occupied the voids within the soil structure (Boardman *et al.*, 2001; Choquette *et al.*, 1987; James *et al.*,
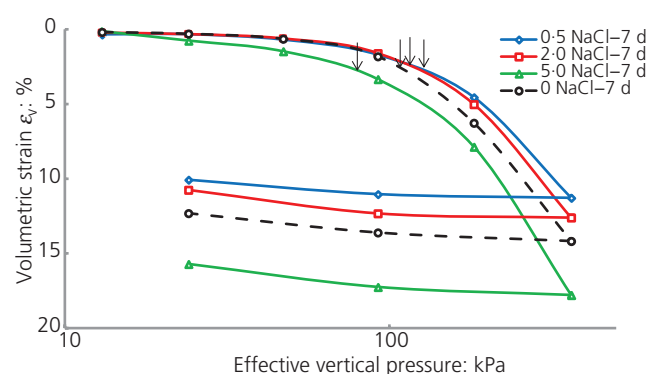
Figure 6. Effect of sodium chloride on the compression behaviour of lime-treated organic clay after 7 d of curing

2008; Rajasekaran and Rao, 1997). The change in structure, in turn, resulted in the increase in shear strength and the reduction in the compressibility of the lime-treated organic clay.

The effect of adding sodium chloride can be further examined by estimating the preconsolidation pressure, p'_c, based on Casagrande's method, as shown in Figure 6. The p'_c values (indicated by the arrows on the compression curves) of 125 and 120 kPa were determined for the lime-treated specimens with 0·5 and 2·0% sodium chloride, respectively. Both p'_c values were larger than the $p'_c = 115$ kPa measured for the specimen with 0% sodium chloride. In contrast, the value of p'_c reduced from 115 kPa for the 0% sodium chloride specimen to 80 kPa when 5·0% sodium chloride was introduced to the lime-treated specimen. Furthermore, the effect of adding sodium chloride to the lime-treated clay containing 1·5% humic acid can be explained by comparing the compression indices, C_c, necessary to predict the amount of primary consolidation settlement. It was recorded that C_c decreased substantially when sodium chloride increased from 0 to 0·5%, which explains why the resistance of lime-treated organic clays to compression improved considerably. For instance, C_c decreases from 0·33 for the lime-treated organic clay without salt to 0·24 for the lime-treated organic clay with 0·5% sodium chloride. In addition, the magnitude of C_c for 0·5 and 2·0% sodium chloride increased from about 0·24 to 0·31. A further increase in C_c was reported at higher sodium chloride (i.e. 5·0%), for which the magnitude of $C_c = 0\cdot37$ was higher than that of the specimen without salt. Based on these results, it is evident that after 7 d of curing, only the specimens containing 0·5 and 2·0% chloride salt improved the compressibility behaviour of the organic lime-treated organic clay with 1·5% humic acid content.

As mentioned previously, due to the presence of salt, the formation of cementitious compounds is enhanced, which in turn decreases the pore space within the accumulation, thus reducing the void ratio. As the voids get filled with cementing materials within the soil phase, the specimen expands outwards during shearing, causing an increase in volume (i.e. volumetric dilation).

Microstructural analysis

SEM and XRD analyses were used to study and record the changes in the soil composition and microstructure of selected specimens of lime-treated organic clay containing added salt. In
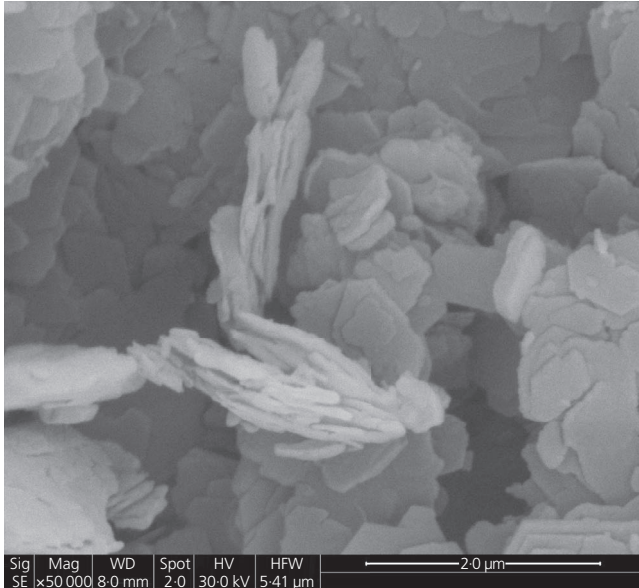
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Figure 7. Soil structure of lime-treated organic clay without addition of sodium chloride

SEM analysis, a secondary electron was used to create the images that enabled the examination of the shape of the soil surface. In previous studies, the alterations in the soil structure as a result of lime stabilisation were visible only through aggregation and flocculation, while the effect on cementation was barely detectable in the SEM images (Al-Mukhtar *et al.*, 2010; Kang *et al.*, 2015, 2017; Mohd Yunus *et al.*, 2013b, 2014, 2015; Petry and Glazier, 2004; Rajasekaran and Rao, 1997; Sakr and Shahin, 2009).

Similar observations were made in the present study. The aggregation and flocculation of clay structure could be observed in the SEM images, as shown in Figure 7. However, the occurrence of cementation products, such as CAH and CSH, in the lime-stabilised organic clay without salt was only evident from the XRD analysis.

Figure 7 presents the micrograph of the organic clay containing 1·5% humic acid and treated with 5% lime (i.e. at the optimum lime content) after 28 d of curing. The stabilisation process typically takes place over the 28 d of curing. At this phase, it is expected that the cementation products such as CAH and CSH have developed in the soil structure. However, the SEM image could not identify the cementing structure of CAH or CSH. The voids in the structure can be seen within the aggregates of the lime-treated organic clay without any salt content, which in turn explains the shear strength reduction (Mohd Yunus *et al.*, 2011, 2012).

Figure 8 presents the SEM images of lime-treated organic clay with 0·5% sodium chloride at two different magnifications of ×5000 (Figure 8(a)) and ×50 000 (Figure 8(b)). As shown in Figures 8(a) and 8(b), the occurrence of cementation within the structure of the soil was evident when the lime-treated samples were stabilised with the addition of sodium chloride. In particular, a closer look at the structure shown in Figure 8(b) (×50 000 magnification) reveals that the plate-like flaky structure, typical of the untreated soil, shown in Figure 7 (×50 000 magnification), was nearly absent. The cementing materials, primarily CSHs, were detected as a fine tubular and a well-knit structure (a needle-like form) that bridged the aggregates together. Choquette *et al.*
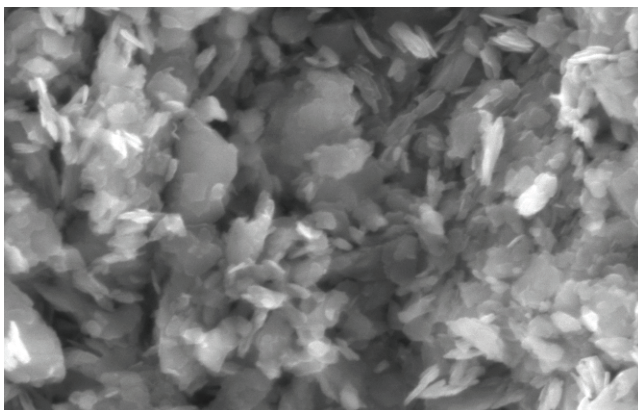
(a)
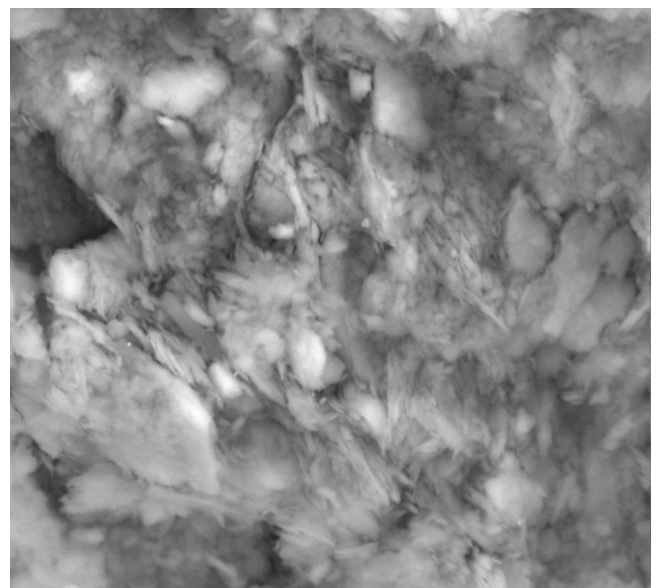
(b)

Figure 8. SEM images of a lime-treated sample with addition of 0·5% sodium chloride at 28 d of curing (a) ×5000 magnification; (b) ×50 000 magnification

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(1987), James *et al*. (2008), Koslanant *et al*. (2006), Modmoltin and Voottipruex (2009), Onitsuka *et al*. (2001) and Rajasekaran and Rao (1997) also observed similar fine tubular and well-knit structures in their SEM studies. It should be noted, however, that the low-magnification image (×5000), shown in Figure 8(a), revealed the appearance of a dispersed structure without a clear evidence of cementation within the soil's structure. This suggests that high-magnification SEM images are more useful for analysing the structure of cementitious materials.

Besides the SEM analysis, the occurrence of cementing materials within the soil's structure was further substantiated with the help of an XRD analysis on replicates of specimens after 28 d of curing that underwent unconfined compressive strength testing (Mohd Yunus *et al*., 2012). Figure 9 presents a typical XRD analysis of lime-treated organic specimens containing sodium chloride. In the XRD analysis, the cementing compounds in the soil specimens were detected by passing a known wavelength through the sample and by studying the diffraction of the wavelength by the crystal lattice that created a distinctive pattern of peaks of reflection with varying intensities and angles. Using the XRD analysis, the presence of CSH was detected at a *d* spacing of 3·04 in the diffraction pattern and two diffraction angles (2θ) of 26·9° for all the specimens (including those with 0% sodium chloride) and 29·355° for the lime-treated organic clay with various sodium chloride contents. Despite this, the related diffraction angle created by the CAH compounds overlapped with that of the other minerals, which increased the possibility of inaccurate identification of the compounds. As a result of this limitation, only the presence of the CSH compound is reported in this study.

Conclusions
In this study, an additional binder was introduced to organic clay in order to improve the deficiencies of the lime stabilisation process. Sodium chloride was used in conjunction with lime-treated organic clay containing 1·5% humic acid. Sodium chloride

was introduced in the amounts of 0·5, 2·0 and 5·0%. The influence of sodium chloride content on the drained and undrained behaviours of lime-treated organic clay can be summarised as follows.

- The triaxial test results presented in this paper validated the effectiveness of adding sodium chloride, which leads to an increase in the negative excess pore water pressure (Δu) and dilative behaviour, ultimately resulting in the enhanced effective strength parameters of organic clay.
- The c' value determined for samples containing 0·5% sodium chloride was equal to 23·6 kPa, which was significantly higher than the value (=7·1 kPa) determined for the samples without any salt (0% sodium chloride). Furthermore, the ϕ'_p of the lime-treated specimens with 1·5% humic acid increased substantially from 20·7° for 0% sodium chloride to 42·4° for 0·5% sodium chloride.
- The optimum salt content (O_{SC}) was determined based on the highest increase in the strength obtained beyond which a decrease in strength was noted. In this study, the behaviour of lime-treated organic clay with addition of sodium chloride indicates that the O_{SC} obtained for the tested clay was equal to 0·5% sodium chloride. It should be noted that the O_{SC} determined was within the range of salt contents used in this study. The consideration of O_{SC} for the lowest amount of salt capable of enhancing the shear strength of clay is always beneficial from an economic and environmental perspective.
- The microstructural analysis conducted in this study showed that the addition of sodium chloride to lime-treated organic clay improved the formation of cementing compounds. The SEM analysis confirmed the same for specimens with 0·5% sodium chloride after 28 d of curing. Moreover, the XRD analysis helped in identifying more areas of high CSH intensity in the sodium chloride-treated specimens in comparison to the specimens without any salt additives.

Figure 9. Diffraction pattern of lime-treated organic clay with various sodium chloride contents

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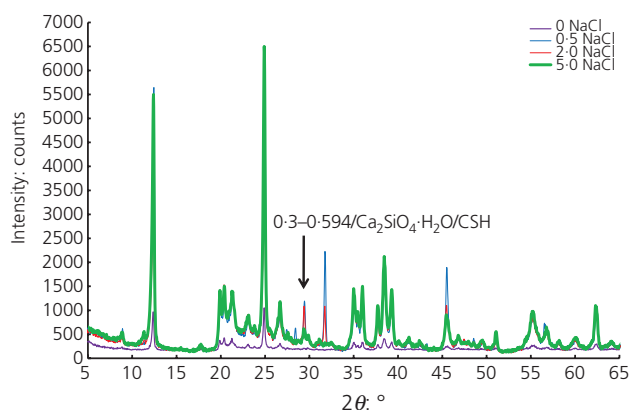Volume 4 Issue GR4

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