2012

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Publication Details
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Ground Improvement
Volume 165 Issue GI4

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ice | proceedings

Proceedings of the Institution of Civil Engineers
Ground Improvement 165 November 2012 Issue GI4
Pages 217–223 http://dx.doi.org/10.1680/grim.11.00025
Paper 1100025
Received 13/07/2011 Accepted 21/03/2012
Keywords: geotechnical engineering/strength & testing of materials

ice
Institution of Civil Engineers
publishing

Variations in strength of lime-treated soft clays

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Strength is often the most significant parameter in measuring the effect of soil improvement in geotechnical engineering practice. In this paper, a primary study is made of the variation in unconfined compressive strength of lime-treated soft clays under various practical conditions. There are three major factors that affect the strength development: lime content, curing time, and curing temperature. The variations in strength with the three factors are analysed and quantified by proposed empirical equations. These equations are verified against experimental data independently. Based on an analysis of the above simulations, a general strength equation is proposed, unifying the influence of all the three factors into a single equation. The capacity of the general equation is demonstrated and it is seen that the proposed strength equations have the potential for predicting the strength of lime-treated clays under various conditions.

Notation

A_w	ratio of lime to clay by weight, both in dry state
$A_{w,max}$	optimum lime content
a	rate of strength increment in the logarithmic t scale
q	shear stress
q_0	strength of the untreated soil
q_{max}	maximum unconfined compression strength
q_{T_0}	strength at $T = 0$°C
T	curing temperature
t	curing time
α_{A_w}	material parameter describing the influence of lime content
α_T	material parameter describing the influence of curing temperature
α_t	material parameter describing the influence of curing time
α_w	material parameter describing the incremental rate of increase in strength with lime content

1. Introduction

Soft clay is encountered in geotechnical engineering practice all over the world. This soil possesses low strength and high compressibility, and thus presents a great challenge to geotechnical engineers, as both the strength requirement and serviceability requirement of upper structures may not be satisfied. As costs of waste disposal, transport and materials procurement continue to increase, the use of ground improvement techniques to prepare soft soils for construction has become much more common. One ground improvement method is the use of lime to improve soft ground, which has been practised since the times of ancient China, Egypt and Rome (e.g. Al-Rawas *et al.*, 2005; Kamon and Bergado, 1991; McDowell, 1959). However, scientific study of the mechanical properties of lime-treated soft clays only started in the 1950s, and it has recently become an important topic for both practitioners and researchers (e.g. Bell, 1996; Locat *et al.*, 1996; Porbaha *et al.*, 2000; Rao and Rajasekaran, 1996). There has been cumulatively a large amount of laboratory and site investigation of the behaviour of soils treated in this way, but there are few systematic and theoretical studies of the mechanical properties of lime-treated soft clay that are applicable to practical problems (e.g. Boardman *et al.*, 2001; Horpibulsuk *et al.*, 2010; Liu *et al.*, 2003, 2010; Locat *et al.*, 1996; Suebsuk *et al.*, 2010, 2011). The lime stabilisation leads to a rise in the pH of the pore water and dissolution of the silica and alumina from the clay, in a manner similar to the reaction between a weak acid and strong base. The hydrous silica and alumina will then gradually react with the calcium ions to form secondary cementitious products that harden with time (Saitoh *et al.*, 1985). The mechanism controlling the strength development of lime-stabilised silty clay has recently been studied by Horpibulsuk *et al.* (2011).

In practice, many laboratory trial mixes are needed to arrive at the appropriate strength before lime stabilisation is undertaken. To be able to determine the proper quantity of lime for stabilisation, a geotechnical engineer needs to understand the variation of strength with various factors such as water content, lime content and compaction energy. In this paper, a primary study of the strength of lime-treated clay is made with the purpose of providing a general and consistent equation useful for representing the strength under various factors. Strength development in lime-treated clay is investigated with respect to three main factors: lime content, curing time, and curing temperature. The variations of strength with the three factors are first independently analysed and quantified via proposed empirical equations. The capacity of the strength equations to represent the strength of different lime-treated soils is demonstrated individually by simulating the unconfined compression strength. The determination of individual equation parameters is also presented and discussed. Finally, a general strength criterion is formulated unifying the influence of all three factors into a single equation. The capacity of the general equation is also demonstrated in the four-dimensional space of strength, lime content, curing time, and temperature. The shear stress parameter q is defined as the difference between the major and the minor principal stresses – that is, $q = \sigma_1 - \sigma_3$. For the unconfined compression condition ($\sigma_3' = 0$), q is the unconfined compressive strength, σ_1.

2. Behaviour of lime-treated soft clays

The introduction of lime to a moist clayey soil induces both physical and chemical changes, resulting in beneficial alterations to its engineering behaviour. Mainly there are four mechanisms of lime–clay–water interaction that are considered to contribute to the modification of material properties. These are (*a*) hydration of lime, (*b*) cation exchange between the pore fluids and the clay minerals, (*c*) flocculation of clay plates to form larger clusters, and (*d*) aggregation of the soil matrix by cementitious precipitates (e.g. Bell, 1996; Croft, 1968; Porbaha *et al.*, 2000). The lime–clay–water interaction is very complicated and the structure formed is generally dependent on the soil's mineralogy, density, acidity and organic content. Generally speaking, the formation of the structure of geomaterials is an extremely complicated process and usually cannot be traced accurately. However, it has been widely observed that the influence of the structure can be represented through some scalar macro-parameters, irrespective of the origin of the structure (e.g. Burland, 1990; Horpibulsuk *et al.*, 2004; Liu and Carter, 1999; Liu *et al.*, 2000). This therefore provides a basis for modelling the mechanical behaviour of geomaterials with structures of various origins in a unified theoretical framework (e.g. Gens and Nova, 1993; Kavvadas and Amorosi, 2000; Liu and Carter, 2003). There is similarity in mechanical properties between lime-treated soils, artificially cemented soils, and natural soils (e.g. Horpibulsuk *et al.*, 2004; Leroueil and Vaughan, 1990; Locat *et al.*, 1996).

In this paper, the peak shear strengths of lime-treated soil under unconfined compression tests are studied by assuming the strength of the parent clay as an intrinsic material property. It may be noted that the addition of lime results in a change in soil mineralogy. Based on examination of a large body of experimental data (e.g. Arabi and Wild, 1986; Bell, 1996; Croft, 1968; George *et al.*, 1992; Kassim and Chern, 2004), the peak strength characteristics of lime-treated clays are investigated in the following sections and semi-empirical strength equations are proposed. These characteristics are also useful for formulating a complete constitutive model of lime-treated soils (e.g. Khalili and Liu, 2008; Liu and Carter, 2002; Schofield and Wroth, 1968).

Some typical experimental data on the variation of the peak strength of lime-treated clays are shown in Figures 1 to 3. In the figures, A_w is the ratio of lime to clay by weight both reckoned in their dry state, t is the curing time, and T is curing temperature in Celsius. The parameter A_w has been used in ground improvement engineering practice and laboratory research for cementation stabilisation. This parameter is therefore used in this paper.

3. Peak strength variation with lime content, curing time and curing temperature

3.1 Peak strength as a function of lime content

The mechanical properties of lime-treated clay are significantly dependent on the lime content. In order to achieve maximum

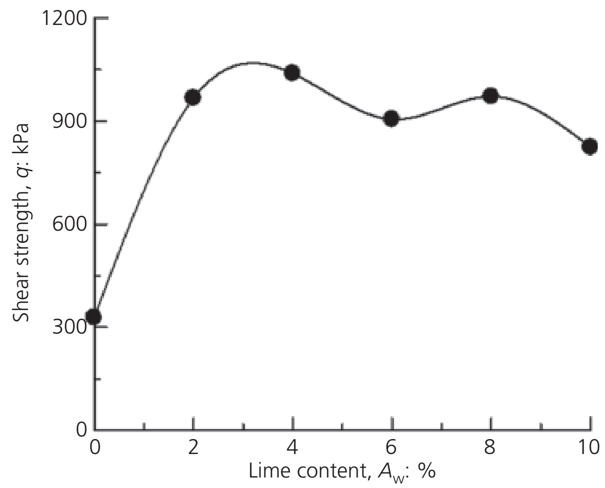

Figure 1. Peak strength of lime-treated kaolin, 28 days of curing (Bell, 1996)

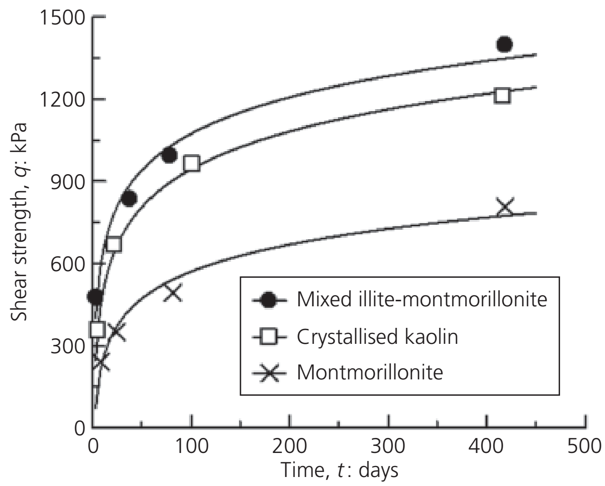

Figure 2. Peak strengths of three soils in normal time scale (Croft, 1968)

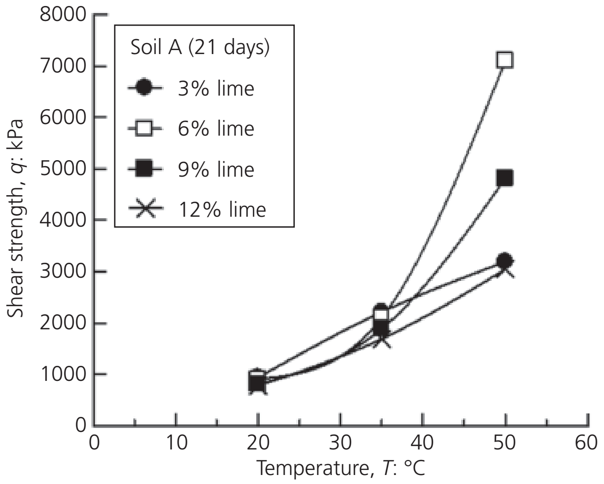

Figure 3. Influence of curing temperature on peak strength (George *et al.*, 1992)

cementation effect, sufficient lime must be added to reach a pH of around 12·4, at which the solubility of the silicates and aluminates of the clay minerals is high enough to produce appreciable quantities of calcium silicate hydrates (CSH) and calcium aluminate hydrates (CAH) in the presence of both the lime and water (Bell, 1996). Addition of lime will generate the high pH values and result in modification of the plasticity indices and reactivity of the clay. With very high lime content, the optimum moisture content in compaction fails to provide sufficient water to allow complete hydrolysis of the lime; this results in the deposition of lime throughout the soil and, as the lime has no appreciable cohesion or angle of internal friction, becomes a detriment to strength. Consequently, there is generally an increase in strength with lime content until peak strength is achieved (at optimum lime content); with further addition of lime, beyond the optimum content, reductions in strength and stiffness are observed. As seen in Figure 1 (Bell, 1996), the peak strength for the soil initially increases with lime content and reaches its maximum value with A_w around 4%. After that, the strength decreases with further increase of lime. It is essential to identify the optimum lime content and the corresponding maximum unconfined compression strength, referred to as $A_{w,max}$ and q_{max}, before any ground improvement method can be designed and the values of $A_{w,max}$ and q_{max} must be identified before any practical work can be carried out. The values of $A_{w,max}$ for many lime-reactive soils are in the range 3–9%; however, $A_{w,max}$ for some clays can be more than 15% (e.g. Arabi and Wild, 1986). An index test on the lime-stabilised clay is useful in practice to determine the $A_{w,max}$, which is designated as the lime fixation point (Horpibulsuk *et al.*, 2011; Kumpala and Horpibulsuk, 2012). As the lime content increases, the plastic limit (PL) of the treated clay increases significantly, while the liquid limit (LL) marginally decreases, resulting in a decrease in the plasticity index (PI) (Thompson, 1966). This decrease in PI indicates the flocculation of clay particles, which is caused by the adsorption of Ca^{2+} ions from cation exchange processes. When the lime content is greater than a transitional content designated as the lime fixation point, the change in PI is minimal. Horpibulsuk *et al.* (2011) found that the lime fixation point is the $A_{w,max}$ value.

As the purpose of any ground improvement measures is to improve the strength and/or the stiffness of the soil, the addition of lime beyond the value of $A_{w,max}$ is counterproductive and wasteful and should be avoided. Therefore, $A_{w,max}$ should selected as a control parameter for engineering practice, and is thus selected as a control parameter for this study. The value of $A_{w,max}$ and the corresponding shear stress q_{max} are identified from the A_w and q relationship, obtained from the conventional unconfined compression tests. The values of soil parameters are related to $A_{w,max}$ and q_{max}. The mechanical properties of lime-treated soil with $A_w > A_{w,max}$ are not considered in this study.

Semi-empirical equations are proposed in this paper to quantify the peak strength variation to provide a useful means to predict the strength of lime-treated clays, and simplicity is one of the requirements in formulating the equations. A linear equation for the peak strength variation with lime content is suggested.

1. $$q = q_0 + \alpha_w A_w \quad \text{for} \quad A_w \leqslant A_{w,max}$$

In Equation 1, q_0 is the strength of the untreated soil and α_w is a material parameter describing the incremental rate of increase in strength with lime content. It is suggested that α_w be determined from the strength of the treated soil at its optimum content – that is, the maximum strength point. Therefore

2. $$\alpha_w = \frac{q_{max} - q_0}{A_{w,max}}$$

Comparison of the simulated and experimental strength data for several treated soils is shown in Figures 4 and 5. The soils used in the simulation were South Wales soil (Arabi and Wild, 1986), a sandy silty clay from Edinburgh (George *et al.*, 1992), and a boulder clay (Bell, 1996). The values of soil parameters are listed in Table 1. The optimum lime content $A_{w,max}$ and the maximum peak shear strength q_{max}, for all the five tests, were measured from the test data. For the sandy silty clay from Edinburgh and boulder clay (Figure 4), the strengths measured at lime contents with $A_w > A_{w,max}$ are also presented. They are, however, not simulated because they are outside the valid range of the proposed equation. As discussed previously, lime content with $A_w > A_{w,max}$ should be avoided in ground improvement practice. The parameter values used in the simulation are determined from the values of $A_{w,max}$ and q_{max}. The calculation of the strength for boulder clay is also done by curve fitting and is shown in Figure 4 by a broken line. It is seen that the simulation from curve fitting gives better representation of the experimental data; however, the simulation from the values of $A_{w,max}$ and q_{max} is also

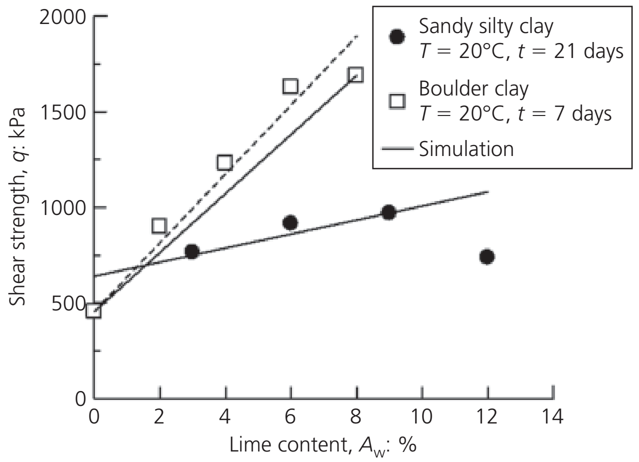

Figure 4. Influence of lime content on peak strength of a sandy silty clay and a boulder clay (data from George *et al.* (1992) and Bell (1996))

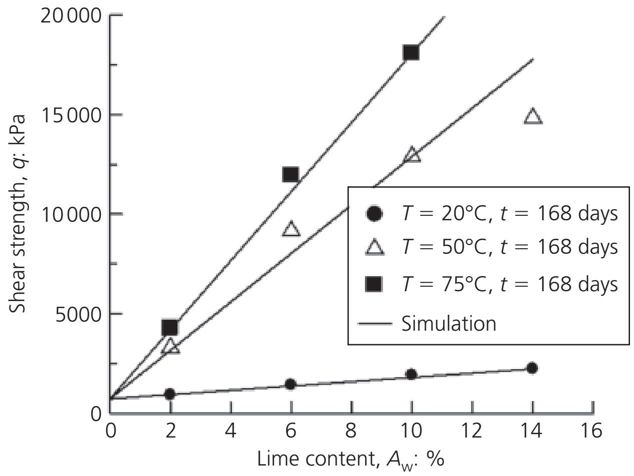

Figure 5. Influence of lime content on peak strength of South Wales soil (data from Arabi and Wild (1986))

acceptable for engineering practice. In Figure 5, the peak strengths of a South Wales soil with lime content with three sets of temperatures are simulated. Overall, the peak strength of this soil is satisfactorily simulated. As seen in Table 1, the value of α_w increases by 15 times for an increment of temperature from $T = 20°C$ to $T = 75°C$, which indicates a non-linear relationship between q and T.

3.2 Peak strength as a function of curing time

As seen in Figure 2 (Croft, 1968), the peak strength of lime-treated soil increases with time monotonically. When q is plotted against $\ln t$ (see Figure 6), the q–$\ln t$ relationship for the same data is essentially linear for different soils. Therefore, the following equation is proposed.

$$q = q_0 + a \ln t \quad (3)$$

The peak strength of the lime-treated soil is the sum of the strength of the untreated soil and the cementation strength of lime stabilisation. The cementation strength increases linearly with $\ln t$; a is the rate of the strength increment in the logarithmic t scale.

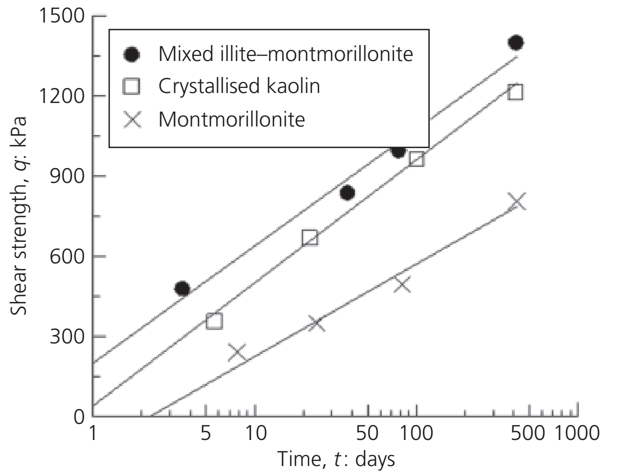

Figure 6. Influence of curing time on peak strength of three soils, simulated and observed.

Comparison of the simulations made by using Equation 3 and experimental data for three treated soils is shown in Figure 6. The tests were performed by Croft (1968) on a mixed layered illite–montmorillonite, a crystallised kaolinite, and montmorillo-

Soil	Test data	q_0: kPa	α_w: kPa	Comments
Boulder clay	Bell (1996)	5	15 400	By definition
		455	18 000	By fitting
Sandy silty clay	George *et al.* (1992)	640	3 670	By definition
South Wales soil	Arabi and Wild (1986)	740	10 740 for $T = 20°C$	By definition
		740	121 600 for $T = 50°C$	By definition
		740	173 300 for $T = 75°$	By definition

Table 1. Values of soil parameters for the influence of lime content

nite. The parameter values are determined by linear fitting and the q_0 value, the unconfined compressive strength at 1 day of curing, is estimated (see Table 2). For the simulated times – that is, for t from 3 days to 420 days – the strength development with time for all the three treated soils is captured well. The valid range of the proposed empirical equation is suggested as $t > 1$.

3.3 Peak strength as a function of curing temperature

As seen in Figure 3 (George *et al.*, 1992), the peak strength increases sharply with curing temperature. For the soil with lime content from 3% to 12%, the strength increment varies from 200% to 700% as the curing temperature increases from 20°C to 50°C. The relationship between strength q and temperature T is proposed as in Equation 4.

4. $$q = q_{T_0} \exp(\alpha_T T)$$

where q_{T_0} is the strength at $T = 0$°C.

Comparison of the simulation made using Equation 4 and experimental data is shown in Figure 7. The tests were performed by Bell (1996). Two soils are considered: boulder clay and Tees laminated clay. For both clays, the curing time is 7 days, lime content is 2% and temperature is from 1°C to 50°C. The values of soil parameters are listed in Table 3. The valid range of the proposed empirical equation is suggested as $T > 1$. It is seen that the influence of the temperature is described well by the proposed exponential relationship.

Soil	q_0: kPa	a
Mixed illite-monotmorillonite	200	190
Crystallised kaolinite	40	200
Montmorillonite	15	120

Table 2. Values of soil parameters for the influence of curing time

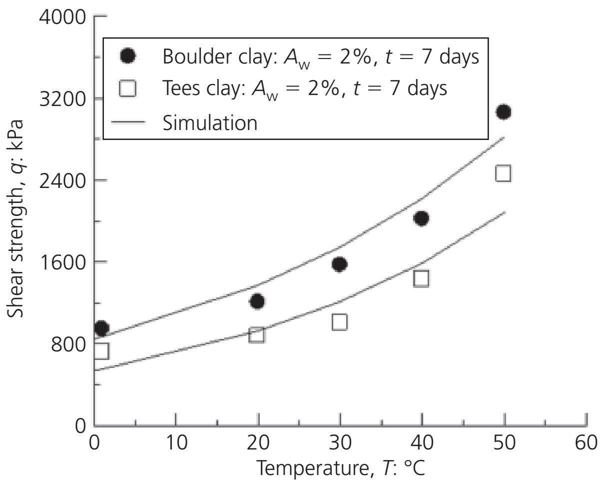

Figure 7. Influence of curing temperature on peak strength of two soils, simulated and observed

Soil	q_0: kPa	α_T
Boulder clay	540	0·027
Tees laminated clay	850	0·024

Table 3. Values of soil parameters for the influence of curing time

4. General strength equation for lime-treated soft clays

The unconfined compressive strength of lime-treated clay is mainly dependent on three factors: lime content, curing time and curing temperature. The influence of these factors has been quantified separately (Equations 1, 3 and 4). It is seen from the comparison of equation simulations and experimental data that the proposed equations capture well the effect of individual factors on the peak strength of lime-treated soils. Based on the analysis presented in the above section, a general strength equation for lime-treated clays is proposed as follows.

5. $$q = q_0(t, T) + \alpha_{A_w} \alpha_t A_w \exp(\alpha_T) \ln t \text{ for } A_w \leqslant A_{w,max}$$

In Equation 5, $q_0(t, T)$ is the shear strength of the untreated soil and α_{A_w}, α_t and α_T are material parameters describing the influence of lime content, curing time and curing temperature on the peak strength of the treated soil, respectively. The range of the material parameters for different lime-stabilised clays can be obtained by the further analysis of more data generated for this specific purpose. If the strength of the untreated soil does not vary with time or temperature, $q_0(t, T)$ is a material constant. This general strength equation (Equation 5) was derived from the three equations (Equations 1, 3 and 4) whose validity was proved by the test results on different lime-treated clays having different clay minerals and pore fluids. The general strength equation is thus formulated on sound principles and may be applied to other lime-treated clays. The parameter values of any studied lime-treated clay must be determined for the simulation. These values reflect the differences in clay minerals and pore fluids.

The application of Equation 5 is illustrated by simulating the experimental data reported by Kassim and Chern (2004). The soil is Pelepas marine clay. The influence of lime content and curing time on soil strength was investigated while the soil temperature was maintained at room temperature, constant around 25°C. As there is no need to consider the effect of temperature, Equation 5 can be simplified as

6. $$q = q_0(t, T) + \alpha_{A_w} \alpha_t A_w \ln t \quad \text{for} \quad A_w \leqslant A_{w,max}$$

The parameter values found are $\alpha_{A_w} = 1380$ kPa, $\alpha_t = 0{\cdot}37$, $q_0 = 24$ kPa. A comparison of the simulations and experimental data in the q–A_w–t space is shown in Figure 8. Overall, the peak strength of Pelepas clay treated with lime is simulated highly satisfactorily. As stated in Section 3.1, only the strength of soil with $A_w \leqslant A_{w,max}$ is modelled for the influence of lime content.

5. Conclusions

Lime stabilisation is an effective method for ground improvement and has been used since ancient times. The improvement of soil strength by lime treatment is studied in this paper. Based on the analysis of a large body of experimental data, it has been shown that the strength of the lime-treated soil is mainly dependent on three factors: lime content, curing time and curing temperature. The variations in the shear strengths with the three factors in unconfined compression tests are analysed and quantified independently using the proposed empirical equations. The validity of the proposed equations has been demonstrated. The variation of strength with the three factors is described satisfactorily by the proposed empirical equations. Finally, a general strength criterion, unifying all three factors into a single equation, is proposed. The validity of the general equation is also demonstrated in the four-dimensional space of strength, lime content, curing time, and temperature. The strength of the lime-treated soil under various conditions can be simulated consistently using the proposed general equation.

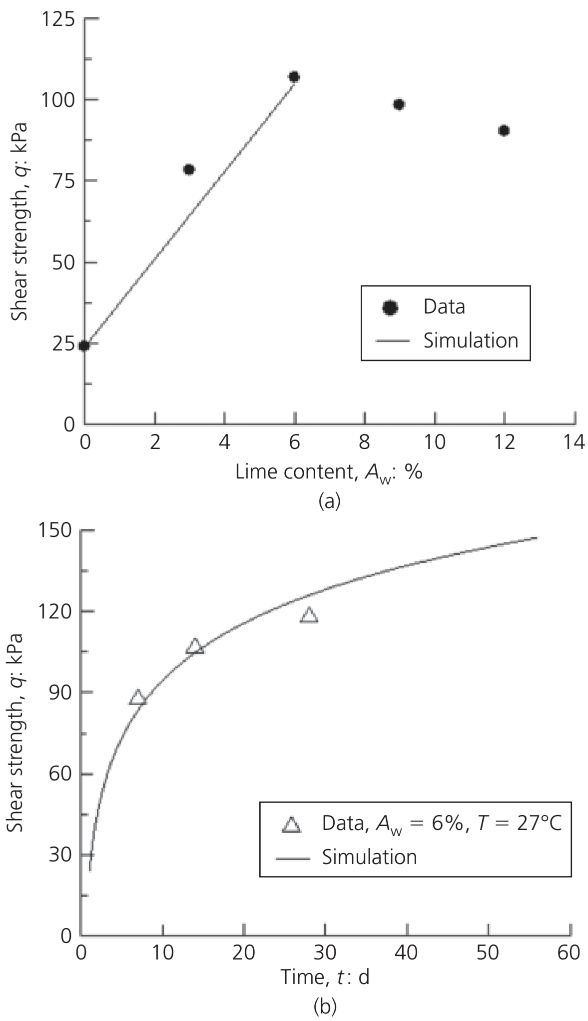

Figure 8. Peak strength of Pelepas clay, simulated and observed: (a) influence of lime content; (b) influence of curing time

Acknowledgement

The authors would like to acknowledge useful work carried out by Mr Stephen Pemberton during his BEng work under the first author's supervision. The authors cannot reach him to obtain his consensus for the authorship of this paper. The third author is grateful to the Suranaree University of Technology for the financial support and facilities provided.

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