1-1-2010

A study of the strength of lime treated soft clays

Martin D. Liu
University of Wollongong, martindl@uow.edu.au

Stephen Pemberton
Wollongong City Council

Buddhima Indraratna
University of Wollongong, indra@uow.edu.au

A STUDY OF THE STRENGTH OF LIME TREATED SOFT CLAYS

Martin D. Liu[1], Stephen Pemberton[2] and Buddhima Indraratna[3]
[1]University of Wollongong, Australia; Tel: +61-2 4221 3035; Fax: +61-2 4221 3238; Email: martindl@uow.edu.au
[2]Wollongong City Council, Australia; Tel: +66-2 524 5523; Fax: +66-2 524 5509; Email: spemberton@wollongong.nsw.gov.au
[3]University of Wollongong, Australia; Tel: +61-2 4221 3046; Fax: +61-2 4221 3238; Email: indra@uow.edu.au

ABSTRACT

In this paper, a comprehensive study of the strength of lime treated soft clays is made. There are three major factors that affect the strength of the soils; they are the lime content, curing time, and curing temperature. The variations of soil strengths with the three factors are analysed and quantified via proposed empirical equations. These equations are verified against experimental data. Finally, a general strength criterion, unifying the influence of all the three factors into a single equation, is proposed. The capacity of the general equation is also demonstrated. It is seen that the proposed strength equations can provide a useful means for predicting the strength of lime treated clays under various conditions.

INTRODUCTION

Soft clay is widely encountered in geotechnical engineering practice. The soil possesses low strength and high compressibility, thus forms a great challenge to geotechnical engineers, particularly in metropolitan areas. As trends in waste disposal, transport and materials procurement costs continue to increase, the use of ground improvement techniques to prepare soft soils for construction has become much more common. The use of lime to improve soft ground has long been used such as in ancient China and Egypt (e.g., McDowell, 1959). The study of the mechanical properties of lime treated soft clays has recently become an important topic for both practitioners and researchers. There has been a large amount of laboratory and site investigation of the behaviour of soils treated in this way, however, there are few systematic and theoretical studies of the mechanical properties of lime treated soft clay, which are applicable for practical problems (e.g., Kamon and Bergado, 1991; Bell, 1996; Horpibulsuk et al, 2010; Indraratna, 2009).

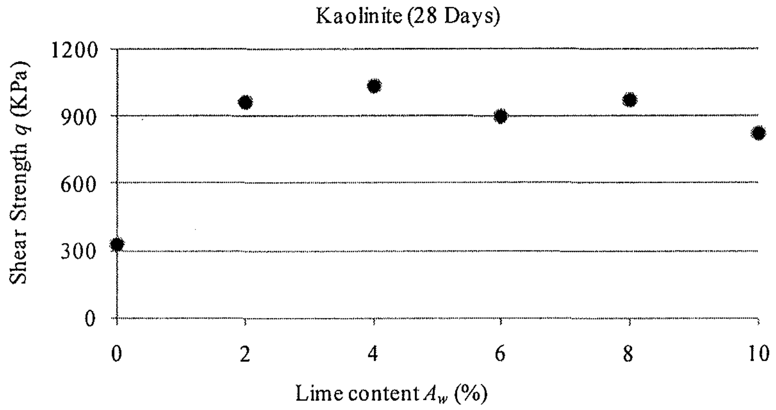


Fig. 1 Peak strength of lime treated Kaolinite (Bell, 1996)

In this paper, a comprehensive study of the strength of lime treated soft clay is made to provide a useful tool for geotechnical engineers. The mechanical behaviour of the lime treated clay under various factors has been investigated and there are three major factors: lime content, curing time, and curing temperature. The variations of soil strength with the three factors are analysed and quantified via proposed empirical equations. These equations are verified against experimental data. Finally, a general strength criterion, unifying the influence of all three factors into a single equation, is proposed. The capacity of the general equation is also demonstrated in the four dimensional space, i.e., strength, lime content, curing time, and temperature.

The stress parameters relevant for soil strength are given here. They are mean effective stress p', deviatoric stress q, and stress ratio η.

$$p' = \frac{1}{3}(\sigma_1' + 2\sigma_3') \quad (1)$$

$$q = (\sigma_1' - \sigma_3') \quad (2)$$

$$\eta = \frac{q}{p'} \quad (3)$$

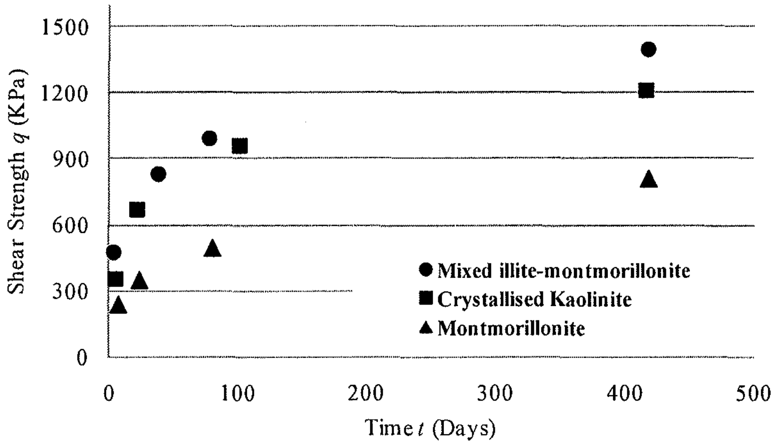


Fig. 2a Peak strengths of three soils in normal time scale (Croft, 1968)

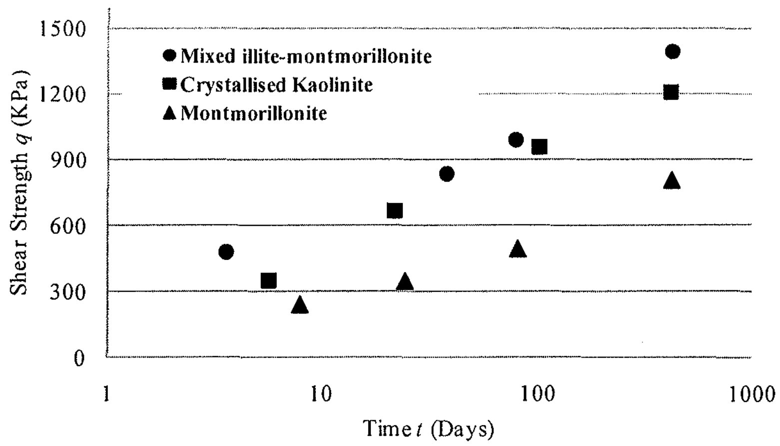


Fig. 2b Peak strengths of three soils in logarithmic time scale (Croft, 1968)

BEHAVIOUR OF LIME TREATED SOFT CLAYS

The introduction of lime and moisture to clay soil induces both physical and chemical changes to the natural soil, resulting in beneficial alterations to its engineering behaviour. Mainly there are four mechanisms of lime-clay-water interaction which have been attributed to the modification of material properties. They are (1) hydration of lime, (2) cation exchange between the pore fluids and the clay minerals, (3) flocculation of clay plates to form larger clusters, and (4) aggregation of the soil matrix by cementitious precipitates (e.g., Croft, 1968; Bell, 1996; Porbaha et al, 2000). The process of the lime-clay-water interaction is very complicated and the structure formed is generally dependent on the soil mineralogy, density, soil acidity and organic content. In this paper the unconfined peak strengths of the soil under triaxial compression tests are studied, specially the variation of soil strength with lime content, curing time and curing temperature. Based on an examination of a large body of experimental data (e.g., Croft, 1968; Arabi and Wild, 1986; Bell, 1996; George et al, 1992; Kassim and Chern, 2004), characteristics of the peak strength of lime treated soft 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. Some typical experimental data on the peak strength of lime treated clays are shown in Figs 1, 2 and 3. In the Figures, A_w is the lime content by weight, t is the curing time, and T is curing temperature in Celsius.

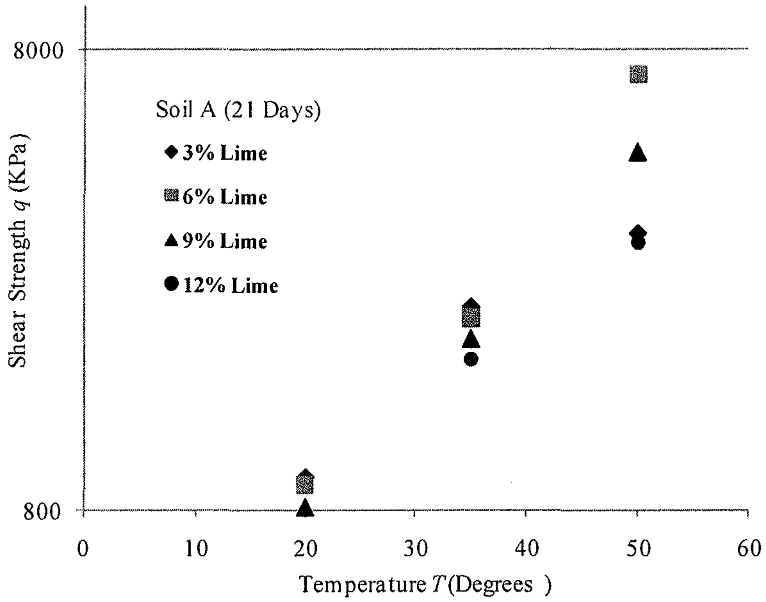


Fig. 3 Influence of curing temperature on peak strength (George et al, 1992)

Peak strength as a function of lime content

For those clays that react with lime, the resulting mechanical properties will be dependent on the lime content. In order to achieve maximum cementation effect, sufficient lime must be added to reach a pH of around 12.4, when the solubility of the silicates and aluminates of the clay minerals is high enough to produce appreciable quantities CSH and CAH in the presence of both the lime and water (Bell, 1996). Addition of lime in quantities less than those generating these high pH values will result only in a modification of the plasticity indices and reactivity of the clay. Further to this, with increasing lime contents, the moisture content required to achieve maximum dry density 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), and with the further addition of lime, beyond the optimum content, reductions in strength and stiffness are observed. As seen in Fig. 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 obviously essential to identify the optimum lime content and the corresponding maximum shear strength, referred to as $A_{w,max}$ and q_{max}, before any ground improvement method can be designed. The values of $A_{w,max}$ for many lime-reactive soils are in the range of 3% to 9%; however, $A_{w,max}$ for some clays can be more than 15% (e.g., Arabi and Wild 1986).

Because 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 $A_{w,max}$ is destructive and wasteful and should be avoided. Therefore $A_{w,max}$ should selected as a control parameter for engineering practice, and is also selected as a control parameter for this study. The mechanical properties of lime treated soil with $A_w > A_{w,max}$ is not considered here. The values of soil parameters are related to $A_{w,max}$ and q_{max}.

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.

$$q = q_o + \alpha_{Aw} A_w \ for \ A_w \le A_{w,max} \tag{4}$$

In the above equation, q_o is the strength of the untreated soil and α_{Aw} is a material parameter describing the incremental rate of increase in strength with lime content. It is suggested that α_{Aw} be determined from the strength of the treated soil at its optimum content, i.e., the maximum strength point. Therefore

$$\alpha_{Aw} = \frac{q_{max} - q_o}{A_{w,max}} \tag{5}$$

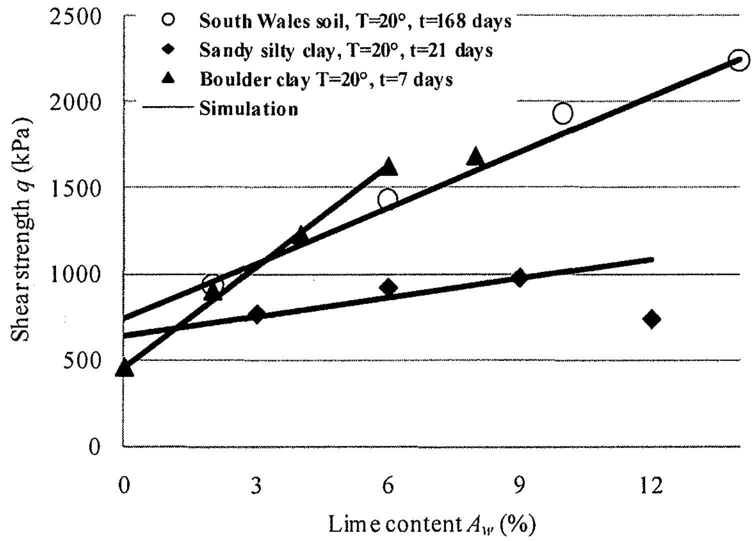


Fig. 4 The influence of lime content on three soils simulated and observed

Comparison of the strength simulated and experimental data for several soils is shown in Fig. 4. The soils used within the simulation were South Wales soil (Arabi et al, 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 three tests were measured from the test data. For the sandy silty clay from Edinburgh and Boulder clay, soil strengths measured at lime contents with $A_w > A_{w,max}$ are also shown within the Fig.4; they are, however, not simulated as they are outside the valid range of the proposed equation.

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

Soil	q_o (kPa)	α_w (kPa)	Comments
South Wales soil	740	10700	q_o by fitting
Sandy silty clay	640	3670	q_o by fitting
Boulder clay	455	19600	by definition

Peak strength as a function of curing time

As seen in Fig. 2a (Croft, 1968), the peak strength of lime treated soil increases with time monotonically. When plotted in a q and ln*t* scale (see Fig. 2b), the relationship between q and ln*t* is essentially linear for different soils. Therefore, the following equation is proposed:

$$q = q_o + a \ln t \tag{6}$$

The peak strength of the lime treated soil is the summation of two parts. The first part is the strength of the untreated soil, and second is the cementation strength of the lime stabilization and increases linearly with ln*t*. *a* is the rate of the strength increment in the logarithmic *t* scale.

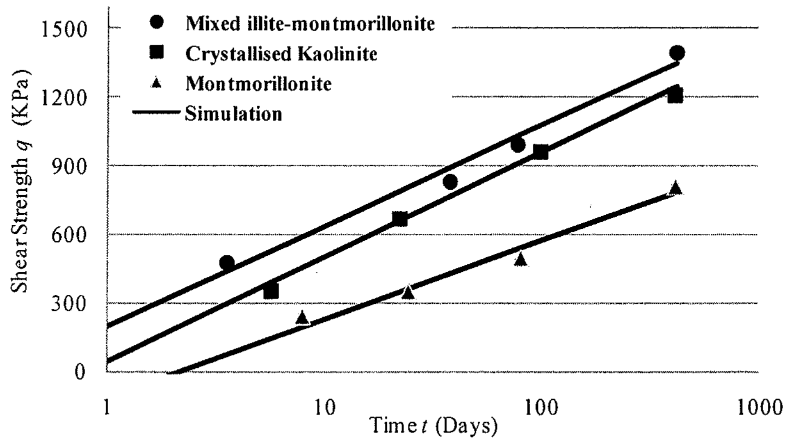


Fig. 5 The influence of curing time on three soils simulated and observed

Comparison of the simulations made by using equation (6) and experimental data for three soils is shown in Fig. 5. The tests were performed by Croft (1968) on a mixed layered illite-montmorillonite, a crystallized Kaolinite, and montmorillonite. The values of soil parameters are determined by a linear fitting and are listed in Table 2. It may be noted the value of q_o identified for montmorillonite is negative. Obviously, simulated undrained shear strength of the soil for curing time around 1 day is not reliable.

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

Soil	q_o (kPa)	a
Mixed illie-monotmorillonite	200	190
Crystallised Kaolinite	40	200
Montmorillonite	-120	150

Peak strength as a function of curing temperature

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

$$q = q_{To} e^{\alpha_T T} \tag{7}$$

where q_{To} is the strength of the soil at $T = 0$.

Comparison of the simulation made by using equation (7) and experimental data is shown in Fig. 6. The tests are performed by Bell (1996). Two soils are considered. They are Boulder clay and Tees laminated clay. For both clays the curing time is 7 days and lime content is 2%. The values of soil parameters are listed in Table 3.

Table 3 Values of soil parameters for the influence of curing temperature

Soil	q_o (kPa)	α_T
boulder clay	540	0.027
tees laminated clay	850	0.024

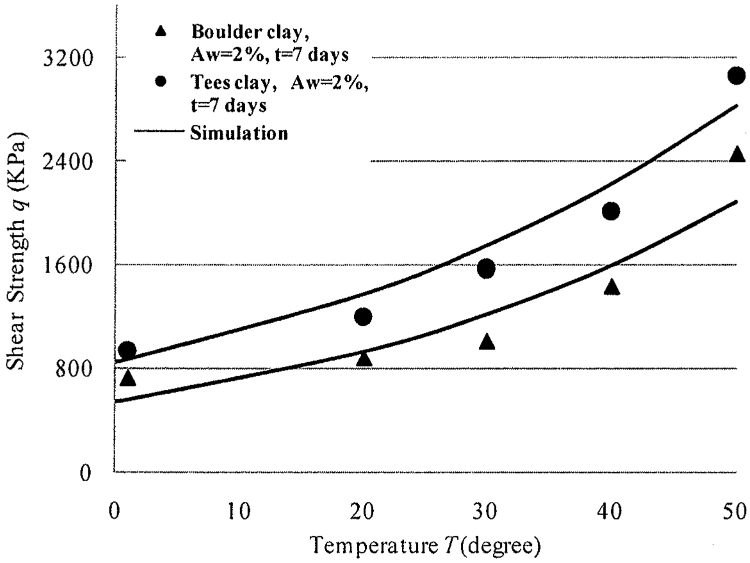


Fig. 6 The influence of curing temperature on three soils simulated and observed

GENERAL STRENGTH EQUATION FOR LIME TREATED SOFT CLAYS

The peak strength of lime treated soil is mainly dependent on three factors such; they are lime content, curing time and curing temperature has been studied. The influence of these factors has been quantified separately, i.e., equations 4, 6 and 7. 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.

$$q = q_o\left(t,T\right) + \alpha_{Aw}\alpha_t A_w e^{\alpha_T} \, Int \;\; for \;\; A_w \le A_{w,max} \tag{8}$$

In Eq. (8), $q_o(t,T)$ is the shear strength of the untreated soil. α_{Aw}, 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. If the strength of the untreated soil does not vary with time or temperature, $q_o(t,T)$ is a material constant.

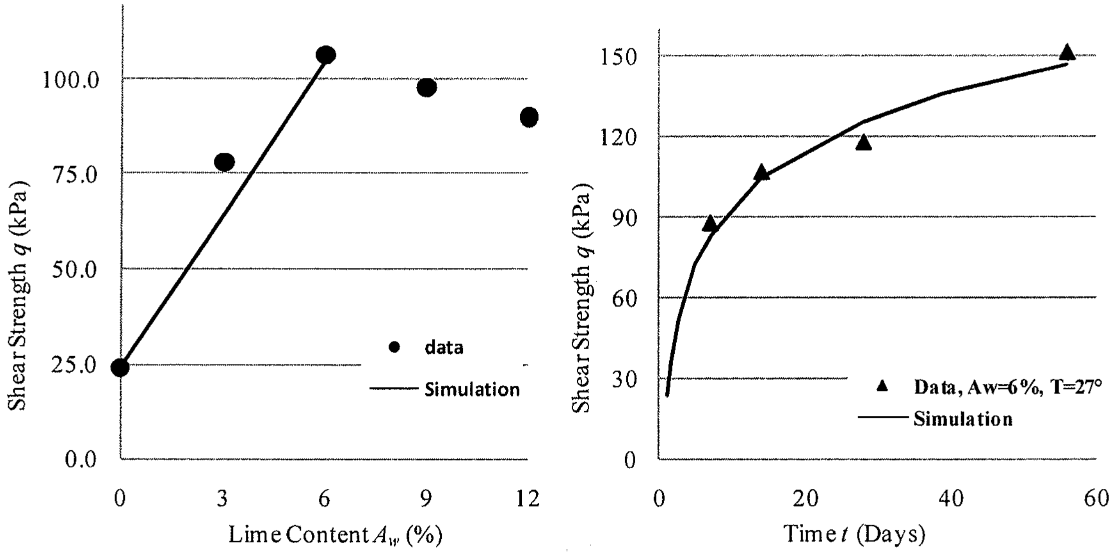
General Eq. (8) is used to simulate experimental data reported by Kassim and Chern (2004). The soil is Pelepas marine clay. The influence of lime content and curing time on soil strength was investigated meanwhile the temperature for the soils were kept at room temperature, constant around 25°. Because there is no need to take into consideration of the effect of temperature, equation (8) can be simplified as

$$q = q_o\left(t,T\right) + \alpha_{Aw}\alpha_t A_w \, Int \;\; for \;\; A_w \le A_{w,max} \tag{9}$$

The values of soil parameters found are: $\alpha_{Aw} = 1380$ kPa, $\alpha_t = 0.37$, $q_o = 24$ kPa. A comparison of the simulations and experimental data in the $q - A_w - t$ space is shown in Fig. 7. Overall speaking, the peak strength of Pelepas clay treated by lime is highly satisfactorily simulated. As stated in previous Section, Peak strength as a function of lime content, only the strength of soil with $A_w \le A_{w,max}$ is modeled for the influence of lime content.

CONCLUSIONS

Lime stabilization is an effective method for ground improvement and has been utilised since ancient times to beneficially modify the engineering behaviour of soft clay soils. The improvement on soil strength by lime treatment is studied in this paper and it has been shown that the strength of the limed treated soil increases significantly with curing time and curing temperature. For the influence of lime content, peak strength is reached at an optimum lime content which for many soils lies within the range of 3 to 9%. The variations in soil strengths with the three factors are analysed and quantified via proposed empirical equations. The proposed equations have been verified against experimental data. Finally, a general strength criterion, unifying all the three factors into a single equation, is proposed. The capacity of the general equation is also demonstrated in the four dimensional space, i.e., strength, lime content, curing time, and temperature.



(a) Influence of lime content (b) Influence of time

Fig. 7 Peak strength of Pelepas clay simulated and observed

REFERENCES

Arabi M. and Wild S. (1986). Mcriostructural development in cured soil-lime composites, Journal of Material Science, Vol. 21, pp.497-503.

Bell F. G. (1996). Lime stabilization of clay minerals and soils, Engineering Geology, Vol. 42, pp.223-237.

Croft, J. B. (1968). The structures of soils stabilized with cementitious agents, Engineering Geology, Vol.2(2), pp.63-80.

George S. Z., Ponniah D. A., and Little J. A. (1992), "Effect of Temperature on Lime-Soil Stabilization", Construction and Building Materials, Vol. 6(4), pp.247-252.

Horpibulsuk, S., Liu, M. D., Liyanapathirana, D. S., and Suebsuk, J. (2010). Behaviour of cemented clay simulated via the theoretical framework of Structured Cam Clay model. Computers and Geotechnics, Vol. 37, No. 1-2, pp. 1-9.

Kamon M. and Bergado D. T. (1991). Ground improvement techniques. Proc. of the nine Asian Regional Conference of Soil Mechanics and Foundation Engineering, Bangkok, Thailand, Vol. 2, pp.526-546.

Kassim K. A. and Chern K. K. (2004). Lime Stabilised Malaysian Clay Soils. Jurnal Kejuruteraam Awam. Vol. 16(1), pp.13-23.

Indraratna, B. (2009). Recent Advances in the Application of Vertical Drains and Vacuum Preloading in Soft Clay Stabilization, 2009 E H Davis Memorial Lecture, Australian Geomechanics Society.

McDowell C. (1959). Stabilization of soils with lime, lime-flyash and other lime reactive materials, High Research Board Bulletin, 231, Washington DC, pp.60-66.

Porbaha, A., Shibuya, S., Kishida, T. (2000). State of the Art in Deep Mixing Technology. Part III: Geomaterial Characterization, Ground Improvement, Vol. 3, pp.91-110.