Hydro-mechanical properties of lime-treated London Clay

Propriétés hydromécaniques de l'argile de Londres traitée à la chaux

Mavroulidou M., Zhang X., Kichou Z., Gunn M.J.
Faculty of Engineering Science and the Built Environment, London South Bank University, 103 Borough Road London SE1 0AA, United Kingdom

ABSTRACT: This paper investigates the effect of lime on the hydromechanical properties of untreated London Clay (a high plasticity clay) and lime-treated and London Clay samples, using two different curing methodologies, and two different dosages of hydrated lime beyond the Initial Lime Consumption level. They were then subject to a number of triaxial tests, to investigate the effect of the above factors on the properties and behaviour of the treated soil in the saturated and partially saturated state. Soil water retention curves were also determined and the favourable effect of the lime on the volumetric stability of the soil demonstrated.

RÉSUMÉ : On étudie l'effet de la chaux sur les propriétés hydromécaniques de l'argile de Londres, à partir d'une série d'essais triaxiaux. On décrit l'effet du dosage en chaux, des conditions de cure et de la saturation partielle. Les résultats expérimentaux indiquent que la chaux a réduit la compressibilité et a amélioré la résistance de cisaillement du sol. Cependant les éprouvettes traitées à la chaux ont affiché un comportement avec radoucissement en grandes déformations, contrairement aux éprouvettes d'argile de Londres qui ont affiché un comportement avec écrouissage positif (durcissement). Ce comportement était particulièrement prononcé dans le cas des éprouvettes à dosage en chaux élevé. Dans la suite on mesure la succion et les courbes de retention d'eau à l'aide de la méthode du papier filtre, démontrant l'effet favorable de la chaux sur la stabilité volumique du sol.

KEYWORDS: lime treated London Clay; hydro-mechanical properties; triaxial testing; soil water retention curve

1 INTRODUCTION

Lime treatment has been extensively used to improve the engineering properties of clay soils; namely to increase the workability of high plasticity soils during construction, and for the stabilisation of roads and pavements (capping layers, sub-bases and subgrades). With these applications in mind, research on lime-stabilised clays has historically focused mainly on properties such as plasticity, CBR or Unconfined Compression Strength (UCS). There is however limited information in the international literature based on triaxial testing that can be used to describe the constitutive behaviour of lime-treated soils. There is also lack of information on the properties of these soils in the partially saturated state, although they are typically compacted and hence, partially saturated. This paper investigates the mechanical properties of a high- plasticity clay (London Clay) and the effect of factors such as lime percentage and curing methodology through CD triaxial tests. Results for the soil water retention curve of this soil are also presented.

2 MATERIALS AND EXPERIMENTAL PROCEDURES

2.1 Materials

The soil used in this study was London Clay taken from an excavation at Westminster Bridge in the city of London and depths corresponding to B2 stratigraphic unit (King, 1981). The soil was air-dried at an average temperature of 22^0C and a relative humidity of 60% for a month and pulverised. Figure 1 shows the particle size distribution of the portion of the soil passing the BS 425 μm sieve. X-ray diffraction (XRD) tests showed 50% Illite, 26% Montomorillonite, 15% Kaolinite and 9% Chlorite (relative % of each clay mineral with respect to clay fraction).

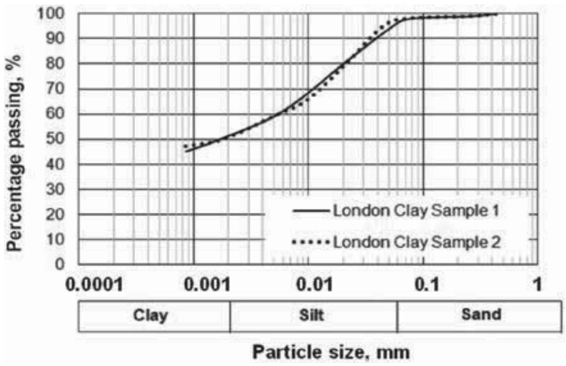


Figure 1. Particle size distribution of the London Clay soil

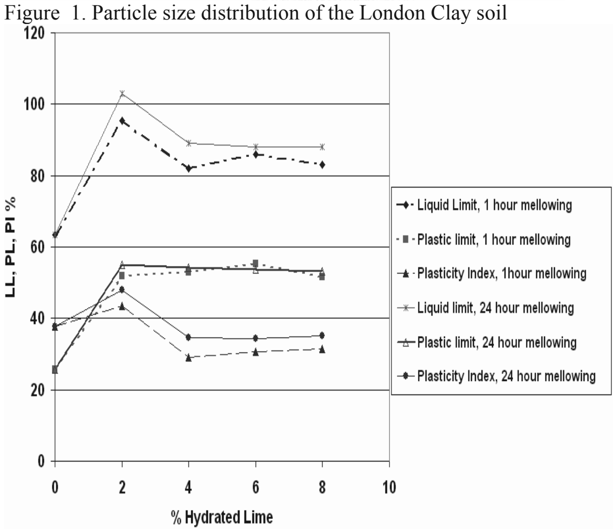


Figure 2. Plasticity characteristics for different percentages of lime

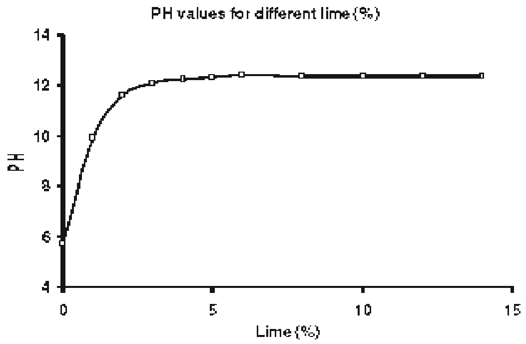


Figure 3. Initial lime consumption (ILC) test.

Commercially available hydrated lime was used after its suitability for soil stabilisation has been established. Chemical analysis on the lime sample carried out in duplicate showed that the relative proportion of calcium hydroxide to calcium oxide was 4.88:1.00. The lime was mixed with clay in dry condition. Plasticity tests were performed on London Clay mixed with lime at percentages of lime of 0%-8% by dry unit of soil respectively, for mellowing periods of 1 and 24 hours respectively. These showed no change in the plasticity characteristics of the lime-treated soil beyond 4% of lime addition (see Fig. 2). Hence this was considered to be the minimum necessary lime percentage for treating this clay. The percentage was confirmed by initial consumption of lime test results (see Fig. 3).

2.2 Specimen preparation

For the preparation of untreated London Clay samples the clay powder was thoroughly mixed with water to achieve a water content of 25.5% (the Proctor optimum) and left to hydrate in sealed bags for 72 h. For the preparation of lime treated samples, dry London Clay and hydrated lime powders were thoroughly mixed and then the required amount of water was added (27% and 32% i.e. dry and wet of Proctor optimum for the lime treated soil). Static compaction was selected as the best way of exerting sufficient control over the compaction process of a clayey soil. In this experimental investigation both types of specimen were compacted at the same target dry density of 1.43 g/cm^3, corresponding to the maximum standard Proctor dry density of the London Clay soil. The compaction of the triaxial specimens (76 mm height and 38 mm diameter) was conducted in split-moulds of the appropriate dimensions. The soil was placed in the mould in six equal layers and compressed at a monotonic displacement rate of 1mm/min until the required height was reached. The loading ram was then held in contact with the soil for another 5 minutes to reduce the rebound upon unloading. A similar method was adopted for the compaction of the specimens for the SWRC tests. These were compacted in standard oedometer cutting rings of 75 mm diameter and 20 mm height used as compaction moulds. After compaction two different methods of curing for the lime-treated specimens were used, namely water curing and air curing. In the first method the specimen was left in the mould to cure in contact with water for the whole curing period. In the air curing method the specimen was wrapped in several layers of cling film and stored in controlled environmental conditions for the specified curing period. To complete saturation after curing, back-pressure saturation was applied regardless of the curing technique.

2.3 Triaxial testing

To assess the effect of cementation, indicative sets of different triaxial testing results will be shown. These were performed on specimens of London Clay and the corresponding lime-treated London Clay specimens prepared and tested at a variety of different conditions. All saturated specimens were sheared drained after isotropic consolidation, following a q/p'=3 path. For the saturated lime-treated specimens results based on two different curing methods (air or water curing), and two different percentages of lime will be shown. For partially saturated specimens, results from four tests will be shown: a) two compacted specimens of a treated (4% lime, air cured) and an untreated soil respectively sheared as compacted (UU test); and (b) two compacted specimens of a treated (4% lime, air cured) and an untreated clay respectively, that were brought to a 300 kPa suction equilisation before testing and subsequently isotropically consolidated under a net stress of 200 kPa and sheared drained following a $q/(p-u_a)$=3 path, maintaining a constant cell pressure and a constant suction of 300 kPa. Axis translation was used to control the suction during testing. The reason for showing results from two different test types was to demonstrate that the effects of cementation were similar, irrespective of the testing conditions.

2.4 Filter paper testing

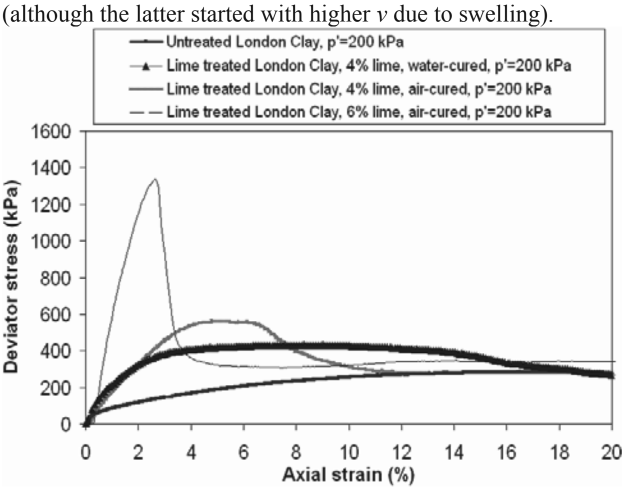
The filter paper used in the present research to measure matric suction ("contact" filter paper technique) was Whatman No.42 filter paper with a calibration formula according to Chandler and Gutierrez (1986). The soil specimen was placed between two Perspex disks. Filter papers were placed on each side of the specimen, between the soil and Perspex disk interfaces. The soil specimens were then tightly wrapped in multiple layers of cling film and sealed bags and left in an insulated environment for one week at a time. After this period the filter papers were carefully removed and their water content was determined. Subsequently, the soil specimens were left for air-drying until the new target water content was achieved. They were then wrapped again for the new moisture content measurement to be performed one week later.

3 RESULTS AND DISCUSSION

3.1 Triaxial testing results

Figures 4 and 5 show indicative comparative stress-strain relationships and volumetric strains of London Clay and lime-treated London Clay specimens (saturated and partially saturated specimens respectively) prepared and tested under various conditions. It can be seen that for all types of tests the London Clay specimens show a strain hardening behaviour for both saturated and partially saturated samples irrespective of the suction level, although there is an increase of strength with increasing suction as expected. Conversely the lime-treated soil shows a strain softening behaviour irrespective of the mode of curing and testing, and this is consistent with the breakage of the cementation bonds. The lime-treated soil became increasingly stiffer, stronger but also more brittle with the increase in lime percentage and also when it was air cured as opposed to water cured. Although the three sets of tests in Figure 5 are not directly comparable due to the different preparation and/or testing procedures adopted, it can still be seen that for the same net stress of 200 kPa, the strength of the lime-treated specimens also increased with suction. In the partially saturated state the brittle behaviour and strain softening of the lime treated specimens was particularly pronounced. Whereas this is the expected behaviour of a partially soil due to the effect of suction in this instance the behaviour is presumably due to the combined effect of suction and the breakage of cementation bonds. Note that for all lime-treated samples (saturated or partially saturated) dilation is clearly observed after, rather than before the peak stress (especially in the 6% air cured samples), i.e. the extra component of strength is not due to the dilatancy as it would be in the case of a particulate material; instead peak strength is mobilised well before the maximum rate of dilation. As dilation only happens upon softening, this could be related to the breakage of cementation bonds and is consistent with the typical behaviour of soft rocks (Vaughan 1993).

Figure 6 shows the stress path plots in the q:p' plane together with the peak (applicable to lime treated soil only) and critical state lines. As for 4% lime the values of M for the lime treated and untreated London Clay were very close irrespective of the mode of curing, it was concluded that both types of soil converged on the same Critical State line in the q:p' plane with M=0.88 (see Fig. 6), i.e. a critical state angle of friction φ'_{cr}=22.5º, consistent with values reported in the literature for London Clay. This implies that this lime content does not appear to have modified the frictional properties of the material. For 6% lime, M and consequently the critical state friction angle were slightly higher (1 and 25.4º respectively), presumably due to the formation of a greater amount of cementing material (due to pozzolanic reactions induced by the surplus of lime above the ILC) coating the particles. The collective characteristics of the soils from the shearing stage are shown in Table 1. The compressibility behaviour of the soils was difficult to assess fully due to the limited range of isotropic compression pressures. The results were complemented with data from K_0 compression using equipment that achieved a range of confining pressures up to 2000 kPa. Even so, full destructuration of the material did not occur. For the ranges of confining pressure considered the increase in stiffness upon lime treatment was very considerable (for instance for the 4% water-cured soil λ=0.05 whereas for the untreated soil λ=0.14). Consequently, during compression lime-treated samples maintained for the most part higher specific volumes *v* than untreated samples (although the latter started with higher *v* due to swelling).



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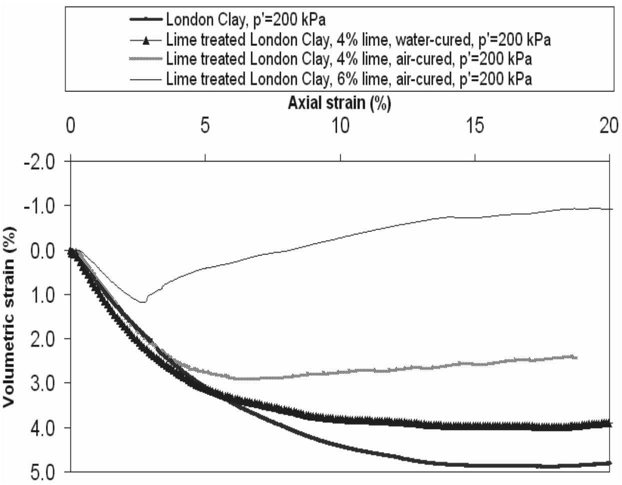
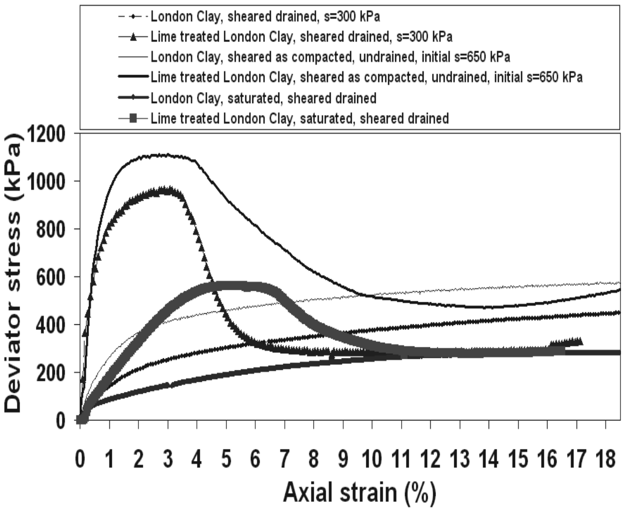


(b)

Figure 4. Indicative triaxial testing results (saturated soil): (a) q:ε_a results (b) ε_v:ε_a results



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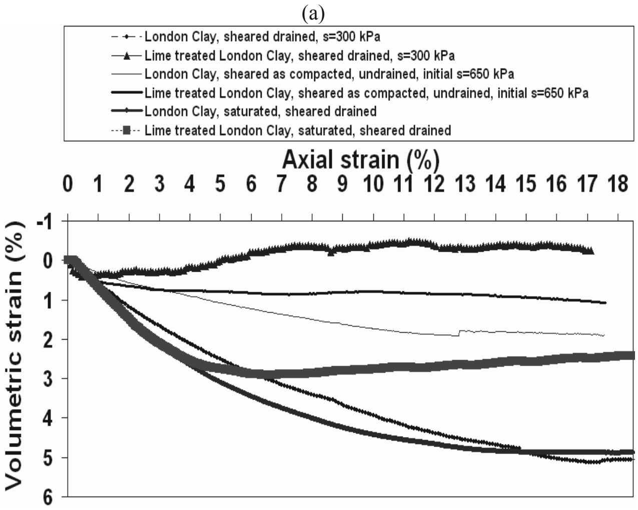

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Figure 5. Indicative triaxial testing results (unsaturated soil, tests performed at a net stress of 200 kPa): (a) q:ε_a results (b) ε_v:ε_a results

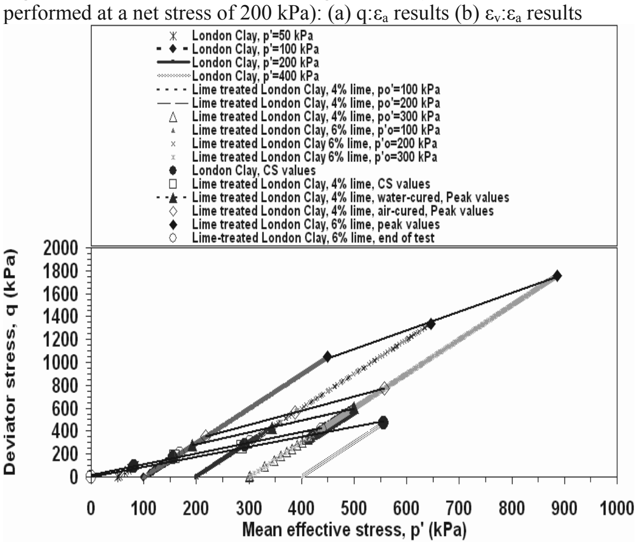


Figure 6. Drained triaxial testing (saturated soils): Stress paths and Critical State and peak state lines in the q:p' plane

Table 1. Collective soil properties derived from the triaxial tests.

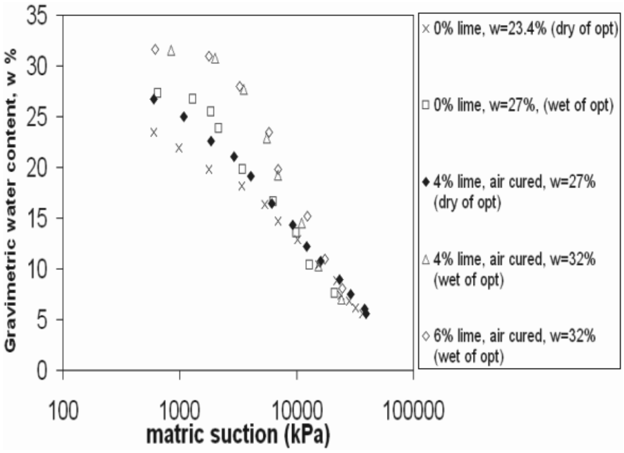
Soil	c'	φ'_{peak}	φ'_c	M
untreated	0	N/A	22.5	0.88
4% lime water cured	38	26.5	22.5	0.88
4% lime, air cured	39	30.7	22.5	0.88
6% lime, air cured	170	39.9	25.4	1

3.2 Filter paper testing results

Figure 7(a) shows the variation of the gravimetric water content with suction. There is an apparent higher overall water retention capacity of the treated soil due to the higher initial water content however it can be seen that the rate of water loss with suction of the lime treated soils is not much different compared to the respective untreated sample, despite the fact that lime has changed the soil structure. Despite the expected change in the nature of the soil (mineralogy and size /specific surface) after treatment, at higher suctions where adsorptive phenomena predominate, the differences between treated and untreated soil are not clear, which is difficult to explain. For the untreated soil it is expected that compaction conditions do not affect the results so much, as at low saturation adsorptive forces gradually predominate and the effect of soil structure appears to have little influence on the SWRC. However it would be expected that the water retention of the chemically treated soils should have been different to that of the untreated soil, due to the change in the composition and specific surface area of the soil (related to the adsorptive forces) brought about by the lime treatment. This is not noticeable in the results of treated sample compacted dry of optimum; there is however some indication that this happens to some extent for the lime-treated soils compacted at higher water content (these show a slightly steaper desorption slope, implying faster desaturation) which could perhaps be attributed to the fact that water facilitated further pozzolanic reactions due to enhanced ion migration, and hence further alteration of the microstructure. As for untreated soils, the lime-treated sample compacted dry of optimum, showed a lower water retention capacity compared to the respective sample compacted dry of optimum due to the more open structure. As with untreated soils, the deformability of the lime-treated samples compacted wet of optimum is higher (see Fig 7c), however the lime treated samples showed overall much lower volumetric strains with respect to the untreated soil, especially for the higher lime content as a result of cementation. Overall it can be clearly noted that cementation considerably affected the strain related quantities (the void ratio and the volumetric strain) due to the increased stiffness.

4 CONCLUSIONS

A number of triaxial tests and filter paper tests were carried out to assess the effect of lime on the hydromechanical properties of statically compacted London Clay and lime-treated London Clay samples respectively. The results showed that the lime-treated soil became increasingly stiffer, stronger but also more brittle with the increase in lime percentage and also when it was air-cured as opposed to water-cured. The strain softening and stiffness degradation at narrow strain ranges was even more pronounced for partially unsaturated air-cured lime-treated London Clay soil was due to the combined effect of lime and suction. It appears that water curing and lower percentages of lime could in fact be more beneficial as they increase sufficiently the stiffness and strength of the soil without resulting in very brittle behaviour and abrupt strain softening within the range of strains of relevance for engineering design. The effect of the lime on the water retention capacity of the material was found to be less pronounced but a considerable reduction in volumetric changes with suction change was noted.



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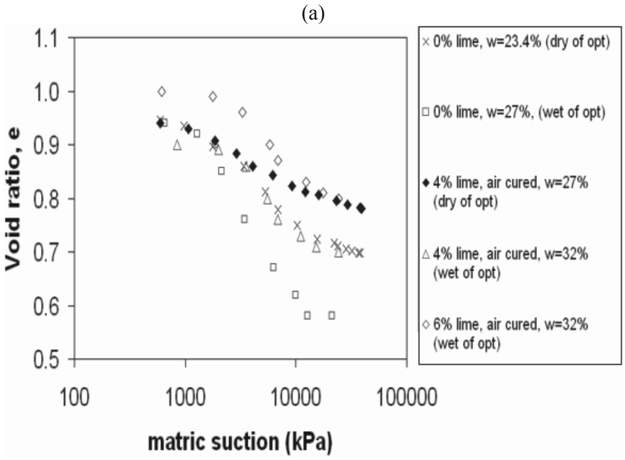

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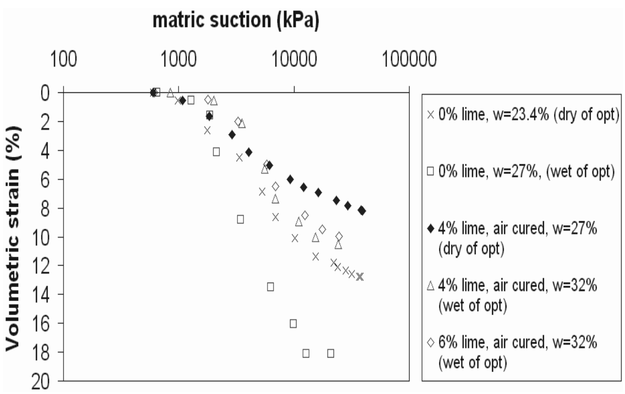

(c)

Figure 7. Filter paper results plotted vs matric suction: (a) gravimetric water content; (b) void ratio; (c) volumetric strain

5 ACKNOWLEDGEMENTS

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