Some Fundamental Engineering Properties of a Lime-stabilized Clay

Certaines propriétés mécaniques d'une argile stabilisée à la chaux

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SUMMARY

This paper gives the results of investigations on some engineering properties of a montmorillonitic clay, stabilized with hydrated lime. Consolidometer test results show an apparent preconsolidation effect, increasing with lime content and curing time, and a slightly unstable structure at pressures exceeding the "preconsolidation load." Beyond the preconsolidation load, lime stabilization causes an increase in pF as compared with that of an unstabilized material at the same moisture content. The permeability decreases with increasing lime content and curing time. Drained shear box tests show that the lime has an immediate effect in increasing the true angle of internal friction, but that long-term gain in strength is achieved mainly through increase in true cohesion.

SOMMAIRE

Les propriétés appliquées d'une montmorillonite stabilisée à la chaux hydratée sont analysées dans cette communication. Des résultats d'essais de consolidation montrent un effet apparent de préconsolidation, augmentant avec la teneur en chaux et la durée du mûrissement ainsi qu'une structure légèrement instable au-delà de la pression de préconsolidation. A même teneur en eau, on constate que lorsqu'on dépasse la pression de préconsolidation, le pF du matériel stabilisé à la chaux est plus élevé que celui du matériel non traité. La perméabilité diminue avec l'accroissement de la chaux et de la durée de mûrissement. Des essais de cisaillement direct ont démontré une augmentation immédiate de l'angle de frottement interne effectif et une augmentation de la résistance à long terme consécutif à une augmentation de la cohésion réelle.

LIME STABILIZATION is a well-known method for improving the road-building properties of clayey soils. The beneficial effects of lime in improving physical properties, as revealed by indicator tests, and in increasing the bearing strength are well known, and need not be elaborated here. There is, however, a lack of knowledge of the fundamental engineering parameters of road-building soils in general, and of stabilized soils in particular. For a rational approach to the problem of road design, a knowledge of these parameters is of paramount importance. In the present study, saturated, or near-saturated samples of lime-stabilized clay were used to evaluate the fundamental parameters concerned. This is a preliminary to the study of the behaviour of non-saturated soils, which are found in road foundations. The properties investigated include consolidation, suction and permeability characteristics, and the fundamental shear-strength parameters.

MATERIALS USED

The soil used was a black clay, a residual soil from the weathering of norite, brought from Onderstepoort, Transvaal. The main mineral constituents are quartz and Ca-montmorillonite, with lesser amounts of hydrous mica, kaolinite, and feldspars. Some of its relevant properties are given in Table I. A high-calcium hydrated lime was used for stabilizing this soil. A typical analysis of the lime is given in Table II. For the main part of the test programme a stabilizer content of 10 per cent by dry weight of soil was used, and in the case of consolidometer tests a few additional samples with 5 per cent and 20 per cent lime were tested. These stabilizer contents may seem high, but are not, when the large amount of clay present and the plasticity of this soil are considered, in comparison with clayey gravels, where a lime content of 3 per cent is frequently used, but where the bulk of the material is coarse and relatively inert.

TABLE I. INDICATOR PROPERTIES OF ONDERSTEPOORT CLAY

	Raw soil	With 10 per cent lime
Liquid limit	70%	77 per cent
Plasticity index	42%	28 per cent
Linear shrinkage	20%	10 per cent
Material $< 2\mu$	57%	
Specific gravity	2.69	
Activity	0.74	

TABLE II. CHEMICAL ANALYSIS OF HIGH-CALCIUM LIME

Total CaO	72.8 per cent
MgO	0.6 per cent
$SiO_2 + R_2O_3$	2.8 per cent
Loss on ignition	23.8 per cent
TOTAL	100.0 per cent
Available lime	67–69 per cent
CO_2	0.5–1.0 per cent

SAMPLE PREPARATION AND TEST PROCEDURE

The clay-lime-water mixtures were prepared in a rotary mixer for approximately one hour. The samples for consolidometer and shear box tests were then cast in flat metal trays, whereas the samples for permeability tests were moulded in 3 in. diam. cylinders. Different densities were obtained by varying the moisture content of the different batches and attempting to mould the samples to a high degree of saturation. The samples were cured in a humid room, at 20 C, for 7 days, 28 days, and 4 months, respectively. After curing, samples of suitable size were cut from the soil cakes. To ensure full saturation, the lime-stabilized samples were soaked under water. Suction was applied gradually at a rate of approximately 1 in. Hg/10 min., up to 24 in. Hg. The suction was then gradually released over approximately one hour, after which samples were cut to the exact size required for testing.

The consolidation tests were carried out on 3-in. diameter, ¾-in. thick samples, in conventional type consolidometres, with incremental loading from 1.8 to 426 lb/sq.in. and then unloading to 1.8 lb/sq.in.

For suction testing, samples were cut from material in the trays, and also from consolidated samples, into rings 1 in. in diameter and ½ in. thick. Referring to the soil suction, or the moisture sorption exponent pF, as introduced by Schofield (1935), the samples were brought to equilibrium at pF = 1 (suction plate), pF = 2, and pF = 3 (pressure plate), and at pF = 4 (pressure membrane). (Croney, Coleman, and Bridge, 1952; de Bruijn, 1963).

The permeability measurements were carried out on the samples mounted in a triaxial cell, providing for back pressure to be applied to the sample to dissolve air (Bjerrum and Huder, 1957). The back pressure was increased in steps up to 80 lb/sq.in., the cell pressure at each step being 10 lb/sq.in. higher than the back pressure.

All shear box tests were done on 3 in. × 3 in. samples, 1½ in. thick, except for those cured for 4 months and consolidated under a normal stress of 66.7 lb/sq.in., where 1½ in. × 1½ in. samples were used. The rate of movement applied was about 0.015 in./hour, and at this rate the time required for shear generally varied between 30 and 78 hours. It is considered that the rate of strain was slow enough to allow pore pressures to dissipate during the shear, so that the samples were classed as fully drained.

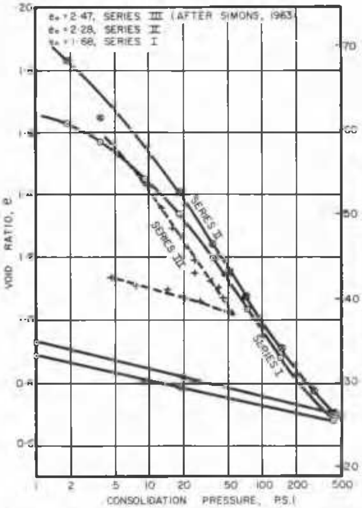


FIG. 1. Consolidation curves for remoulded Onderstepoort clay.

TEST RESULTS

Consolidometer Tests

In Fig. 1 are shown load-settlement curves for remoulded, unstabilized Onderstepoort clay, consolidated from initial moisture contents of 62 per cent (e_0 = 1.68, series I) and 85 per cent (e_0 = 2.28, series II). These curves, as also the time-settlement curves on which they are based, are typical for remoulded clays, and do not call for further comment. As a comparison the load-settlement curve for remoulded Onderstepoort clay of slightly higher plasticity index is given (series III) as arrived at by Simons (1963).

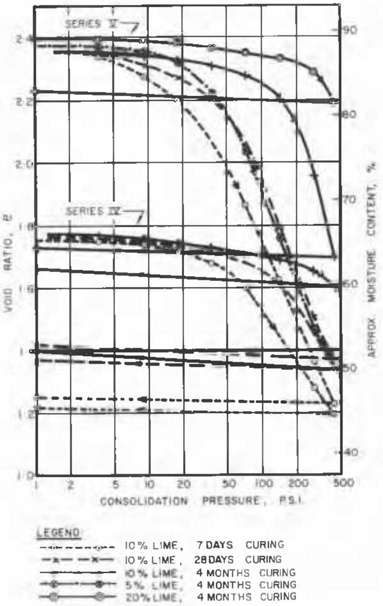


FIG. 2. Consolidation curves for Onderstepoort clay, stabilized with 5, 10, and 20 per cent hydrated lime, and cured for 7 days, 28 days, and 4 months.

The load-settlement curves for lime-stabilized soil, consolidated from initial moisture contents of 66 per cent (e_0 = 1.78, series IV) and 88 per cent (e_0 = 2.37 series V), are shown in Fig. 2. As expected, the stabilization and setting of the soil-lime causes a preconsolidation effect, the apparent preconsolidation load increasing with stabilizer content and curing time. A slightly unstable structure is indicated in that the compression index C_c, once the preconsolidation load is exceeded, is larger for the stabilized materials than for the unstabilized soils and, as is also expected, this tendency increases with stabilizer content and curing time. The condition is analogous to the one experienced with overconsolidated quick clays. This concept is illustrated in Fig. 7(a), indicating how the preconsolidation load, p', at moisture contents w_1 and w_2 increases with curing time t, but that once the preconsolidation load is exceeded, the load-settlement curve tends towards the virgin compression curve as given by normal consolidation. The time-settlement curves are as normal in the ranges both below and above the preconsolidation load.

Suction Properties

As pointed out by Croney, Coleman, and Bridge (1952), consolidometer test results can be used for determining the relationship between suction and moisture of saturated samples. Water leaves the soil during consolidation and enters during offloading, until the suction of the moisture retained is equal to the applied pressure. This concept has been used in Fig. 3, where some of the consolidation curves from Figs. 1 and 2 have been transformed to a moisture-pF scale. These curves are then compared with the respective suction-moisture curves as obtained by the suction tests at pF = 1, 2, 3, and 4. Curves which are directly comparable, are joined by arrows (i.e., series B, E, and F). All samples were tested in desorption (indicated by arrows on the curves).

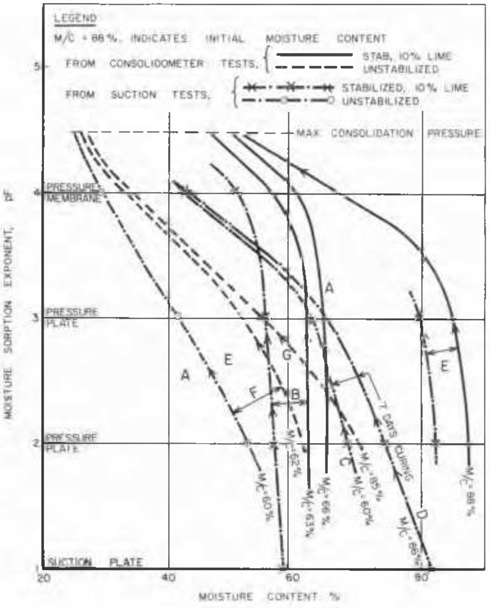


FIG. 3. Moisture-suction curves for Onderstepoort clay, and for clay stabilized with 10 per cent hydrated lime. Curing time; approx. 28 days, except where otherwise stated.

It is interesting to note that good agreement exists between the curves obtained by suction tests, and the respective ones obtained from consolidometer results, except that the former ones are a little "drier." This effect is often noticed in natural soils and is ascribed, *inter alia*, to the resistance against displacement offered by individual soil grains or grain aggregates undergoing desorption in the consolidometer. The analysis of the phenomenon has received attention by several authors in later years (de Bruijn, 1963).

From Fig. 3 it is seen that, for the stabilized samples, the moisture content is affected relatively little by the pressure applied, as long as this is below the preconsolidation load. Beyond this range, however, the moisture content is primarily dependent upon the pressure, and is conspicuously higher for the stabilized samples than for the unstabilized ones.

Permeability

From the consolidometer test data, the saturated permeability, *k*, can be evaluated (Taylor, 1948). The permeabilities thus determined, together with permeameter test results are given in Fig. 4, showing that the permeability is decreased when stabilizing the clay with lime. Again this effect is more pronounced with increasing lime content (not shown) and curing time.

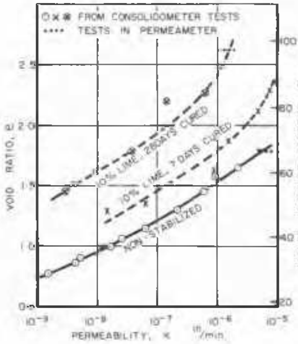


FIG. 4. Void ratio-permeability curves for Onderstepoort clay, and for clay stabilized with 10 per cent hydrated lime, and cured for 7 days and 28 days.

It is accepted that for most soils, the finer the soil and the smaller the pores, the higher is the suction and the lower is the permeability, provided the moisture content, or conversely, the dry density, is the same. The results in Figs. 3 and 4, indicate, thus, that lime stabilization reduces the pore size of the clay. Possible reasons for this may be the formation of gels "clogging up" the pores, and also the formation of a cemented matrix, caused by the reaction between lime and clay. In view of Fig. 4, the latter cause would appear to be most likely.

Shear box tests

This test programme was carried out to evaluate the fundamental shear-strength parameters as defined by Hvorslev (1937) in the equation:

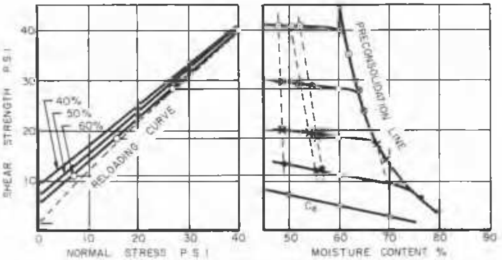
$$\tau_f = c_e + \sigma'_f \tan \phi_e, \qquad (1)$$

where τ_f = shear strength, c_e = true cohesion, σ'_f = effective normal stress at failure, ϕ_e = true angle of internal friction. The determination of these parameters in saturated soils involves comparing the strengths of samples at the same moisture content, or the same density, but with different effective stresses acting on the failure plane at failure. It should be noted here that Hvorslev's concept implies that, for a natural saturated soil, the true cohesion is a function of the water content only, the difference in shear strength under different normal stresses being a function of the true angle of internal friction. This concept has to be modified when stabilizers are added to the soil, as the true cohesion and also the true angle of internal friction will vary, *inter alia*, with stabilizer content, curing time, and curing conditions. It is believed, however, that Hvorslev's concept is still valid provided these latter factors are kept constant, and the following analysis is based on this.

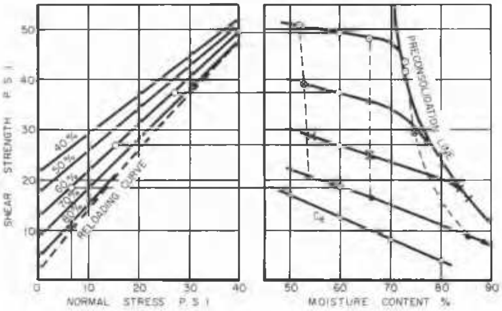
When sheared under drained conditions, it is a normal occurrence for loose sands and normally consolidated clays to settle, and for dense sands and heavily overconsolidated clays to swell, immediately before, and at the time of failure. Such a change of volume during shear signifies the addition or expenditure of energy, a concept formulated by Bishop (1950) for sands and extended by Gibson (1953) and others for clays. Applied to shear box testing the correction to the shear strength is

$$\tau_d = \sigma'_f(\Delta y/\Delta x), \tag{2}$$

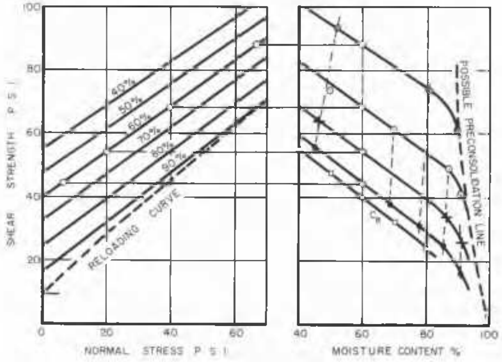
where Δy is the vertical displacement accompanying the horizontal displacement, Δx, at the stage of failure. In the present investigation, where many of the samples are heavily overconsolidated (Fig. 2), for the normal stresses applied during shear, and where the soil structure is slightly unstable at normal stresses above the preconsolidation load, the energy corrections become very significant, and do in some cases amount to 25 per cent of the "correct" shear strength value.



(a) 7 DAYS CURING



(b) 28 DAYS CURING



(c) 4 MONTHS CURING

SAMPLES WERE CONSOLIDATED AND SHEARED UNDER NORMAL STRESSES THUS

•	×	+	⊗	⊙	◎	□
6·7 P.S.I.	15·5 P.S.I.	20·0 P.S.I.	26·7 P.S.I.	40·0 P.S.I.	66·7 P.S.I.	TRUE COHESION

FIG. 5. Shear strength *vs.* moisture content and normal stress relationships for Onderstepoort clay, stabilized with 10 per cent hydrated lime, and cured for 7 days, 28 days, and 4 months.

From shear tests carried out on saturated samples, a family of lines, depicting shear strength as a function of moisture content and applied normal stress can be obtained. This method of analysis is shown in Fig. 5 (right). It can be most readily applied when the same set of normal stresses is used for a whole series of samples, and involves relating shear strength to moisture content of samples sheared under the same normal stress. From these iso-lines, a family of lines can be drawn, giving true cohesion and true internal friction at different moisture contents (left diagrams, Fig. 5). From the normal stress *vs.* shear strength diagrams, the value of the true cohesion can be transformed back as a final iso-line on the moisture content-shear strength diagram. A feature of the iso-lines to the right in Fig. 5, is the existence of the preconsolidation line, an upper limit of the shear strength-moisture content relationship, which is not determined by the normal stress during shear, but by the preconsolidation load. The existence of this unique relationship is well known for normally consolidated clay samples, and for samples subjected to a common preconsolidation pressure (Henkel, 1960). It is interesting to note that the latter kind of relationship is also valid for stabilized clays, which are artificially preconsolidated because of cementation. Corresponding to the preconsolidation line on the strength-moisture plot, there exists a lower limit on the

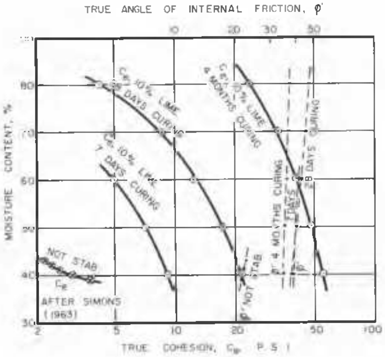


FIG. 6. Moisture content *vs.* true cohesion and true angle of friction for Onderstepoort clay, and for clay stabilized with 10 per cent hydrated lime, and cured for 7 days, 28 days, and 4 months.

normal stress-shear strength diagram. This line, which is slightly curved, shown with dotted lines on the left diagrams of Fig. 5, is analogous to the reloading shear-strength curve of preconsolidated clays (Hvorslev, 1960).

Fig. 6 gives the shear test results, as compared with test results for unstabilized, remoulded Onderstepoort clay (Simons, 1963). It can be seen that adding lime to the clay has an immediate effect in increasing the true angle of internal friction; indeed 10 per cent lime nearly doubles the friction angle after 7 days' curing. Prolonged curing has little effect on the true angle of friction, in fact it is slightly reduced after 4 months' curing. Lime also increases the true cohesion of this clay, an effect which increases with lime content (not shown) and curing time. Thus, after 4 months' curing of samples with 10 per cent lime, the true cohesion is 6 to 8 times as large as the values at 7 days, at the same moisture contents. It is clear that lime has an immediate effect in increasing the true angle of internal friction, but that long-term gain in strength is mainly achieved through increase in true cohesion.

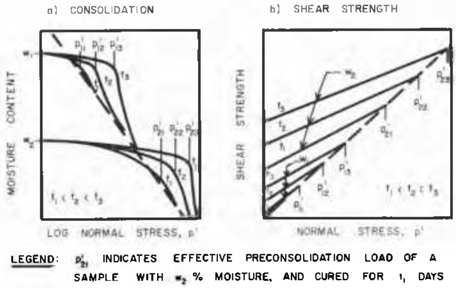


FIG. 7. A concept of how the shear-strength behaviour of a stabilized soil is related to the consolidation characteristics.

In Fig. 7 a concept is outlined of how the shear strength behaviour of the stabilized soil is related to the consolidation characteristics. Although this picture is well known from studies of sensitive clays, in the present case the curing time (and stabilizer content) give rise to variation of the preconsolidation load and the true shear-strength parameters, in spite of the moisture content being the same.

CONCLUSION

The present paper has served to illustrate that lime-stabilized clays in the saturated state can be analysed in terms of generally accepted concepts in regard to consolidation characteristics, suction, permeability, and shear strength. The clay behaves like a preconsolidated material and does so because of the cementation of particles, an effect increasing with stabilizer content and curing time.

The work described is considered to be a preliminary to the study of non-saturated, stabilized materials, but is considered important in establishing fundamental parameters. It seems clear that, for further progress in certain aspects of pavement design, a clear knowledge and understanding of such fundamental properties is very important.

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