THE BRITTLE BEHAVIOUR OF NATURALLY CEMENTED SOILS

COMPORTEMENT CASSANT DES SOLS NATURELLEMENT CIMENTES

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Synopsis

The mechanical significance of cementation is studied by means of a laboratory test programme involving three Canadian clays. An initially elastic stress-strain behaviour is observed under triaxial compressive loading at low test pressures, and the cementation bond strength is essentially independent of effective stresses. At higher test pressures an 'unstructured' effective strength parameter ϕ' is defined.

The fissured nature of the soil structure can lead to a significant scattering of strength data. This occurs in tests where an absence of confining pressure enables a tensile stress system to be developed in the soil, as in indirect tension and unconfined compression tests on soaked specimens. It is concluded that strength test results cannot be simply treated in terms of classical behaviour theories, and that a re-evaluation of design procedures for bonded soils may be required.

Introduction

In a number of publications, reference has been made to the development and possible significance of cementation bonds in Leda clay and other Eastern Canadian clays. Such bonds are considered to develop during deposition of the clay (Crawford 1963), and are probably a result of the existing chemical environment, both past and present. It has been suggested (Townsend 1965, Kenney, Moum and Berre 1967) that cementation results from the formation of calcium or iron compounds at individual particle contacts as the soil profile is developed.

The mechanical significance of structural cementation has been discussed by several authors, and is the subject of study in this Paper. It is commonly represented by a significant tensile strength (Conlon 1966) or by a large 'cohesion' intercept when the Mohr-Coulomb failure envelope is obtained (Crawford 1963). Behaviour in the tensile stress region is of some interest; for example, the tensile strength of bonded clay has been treated in terms of the Griffith Crack Theory by Townsend (1967). Of more immediate concern, however, is the influence of bonding on the compressive stress-strain-time characteristics of a cemented clay.

In describing and analysing a landslide on the Toulnustoc River in Quebec, Conlon (1966) discussed the importance of cementation strength and its subsequent breakdown under the application of shearing stresses. He concluded that "the shear strength ---- may not be defined adequately by classical shear strength failure criteria". Both Conlon and Kenney (1966) have described the effect of strain on the cohesive and frictional components of shearing resistance in a bonded clay. Such clays may also exhibit a significant time-dependency of strain (Crawford 1965). Walker and Raymond (1968) have concluded that rates of consolidation are greatly affected by structural cementation.

Materials and Testing Programme

In view of the above considerations, a detailed programme was initiated to study the mechanical properties of cemented clays, and the relevance of these properties to certain field situations. Block samples of three clays have been used in the laboratory work - a Leda clay taken from the site of a natural slide in the Ottawa area, a varved clay from the Mattagami area in Northern Quebec, and a Labrador clay similar to that used by Kenney, Moum and Berre (1967). The basic chemical, mineralogical and engineering properties of these clays are given in Table 1.

Property		Leda Clay	Mattagami Clay	Labrador Clay
Water Content	w	45%	80%	34%
Liquid Limit	w_L	42%	78%	27%
Plastic Limit	w_P	22%	24%	20%
Liquidity Index	I_L	1.15	1.04	2.0
Plasticity Index	I_P	20	54	7
Percent clay fraction	%	55%	80%	55%
	pH	8.0	8.0	9.0
Salinity 0/00		0.6%	0.6%	1.3%
Mineralogy (clay fraction)				
Hydrous Mica		50-60%	50-60%	60%
Iron Chlorite		10-15%	Abund.	10-20%
Vermiculite		6%	5%	-
Montmorillonite-type		trace	-	(2-5%)
Quartz & feldspar		15-20%	Abund.	10-20%
Activity		0.36	0.67	0.13

Table 1 - Soil Properties

The laboratory tests performed on the three clays consisted of unconfined indirect tension (Brazilian) tests on soaked specimens, unconfined triaxial compression tests on both soaked (in water) and unsoaked (in air) specimens, isotropic triaxial consolidation tests, and consolidated drained and undrained strain-controlled triaxial tests, which included some cyclic loading tests.

All consolidated triaxial shear tests were performed in Geonor cells fitted with rotating bushings to minimize piston friction, and base transducers for pore pressure measurement. Strain rates were chosen to ensure 95% dissipation (or equalization) of excess pore water pressures at the chosen stress level (usually 15% of the failure stress).

In order to emphasize the overall behaviour, only data from tests on Leda clay will be presented and discussed in detail. The results involving Mattagami and Labrador clays will be summarized briefly in a separate section. This is particularly necessary since, in one respect, the observed behaviour of Labrador clay is different from that reported for Leda clay.

Stress-Strain Behaviour

Figure 1 shows typical stress-strain curves obtained from two consolidated triaxial shear tests on Leda clay. Both samples were subjected to effective consolidation pressures less than the apparent preconsolidation pressure (p_c), the value for sample LE2 being twice that for sample LE1. Both samples exhibited a peak stress-difference at a very low strain, however their post-peak behaviour differed

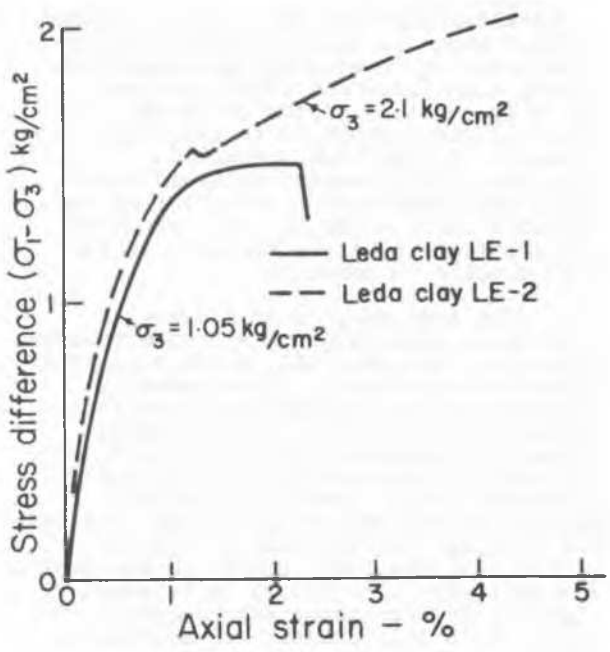

Figure 1 - Stress-strain behaviour for naturally cemented soils.

considerably. Sample LE1 suffered a rapid reduction in shear resistance, failure being associated with the development of planes of rupture in the specimen, while sample LE2 exhibited a second peak after large strains. All undrained stress-strain curves were similar to LE1 for consolidation pressures less than p_c, however the drained curves varied from type LE1 to type LE2 as the consolidation pressure approached p_c.

Such behaviour has been explained in some detail by Conlon (1966), who separated the strain-dependency of the cementation bonding and the frictional resistance which was considered to be directly proportional to the effective consolidation pressure. At low stresses (LE1), the cementation dominates, and little frictional resistance is left once the bonding is destroyed. Higher stresses (LE2) enable sufficient resistance to be built up to enable the stress-strain curve to continue rising after the initial peak caused by the breakdown of cementation. At very high stresses, purely frictional effects dominate and a single peak at large strains is obtained, failure being observed as a fairly uniform bulging of the specimen.

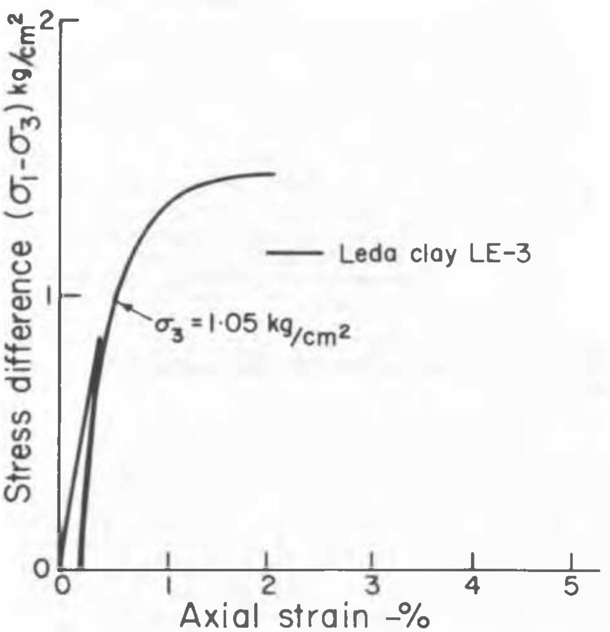

Figure 2 - Stress-strain behaviour in a cycle of loading for a naturally cemented soil.

Associated with the brittle behaviour of the cemented soil structure at low stresses is the possibility that it may be treated as elastic in deformation up to peak strength . Figure 2 presents data from one of the undrained triaxial tests (LE3) performed on Leda clay to study the response of the soil structure to cyclic loading. The consolidation pressure for this test was 1.05 kg/cm^2, and the sample was cycled once at about 50% of the eventual failure stress. Both the initial and cyclic moduli of deformation are high (200 and 400 kg/cm^2 respectively) and the irrecoverable (plastic) strain is small in magnitude. The possibility exists that this plastic strain may be partly due to sample disturbance (Ward, Samuels and Butler 1959), which effect would diminish the modulus on first loading.

Pore pressure changes during the cyclic loading were closely equal to 1/3 of the applied stress difference, and were recoverable after cycling of this stress. It is therefore likely that the soil in-situ will, to a fair approximation, behave elastically under load providing the peak strength of the cementation bond is not exceeded.

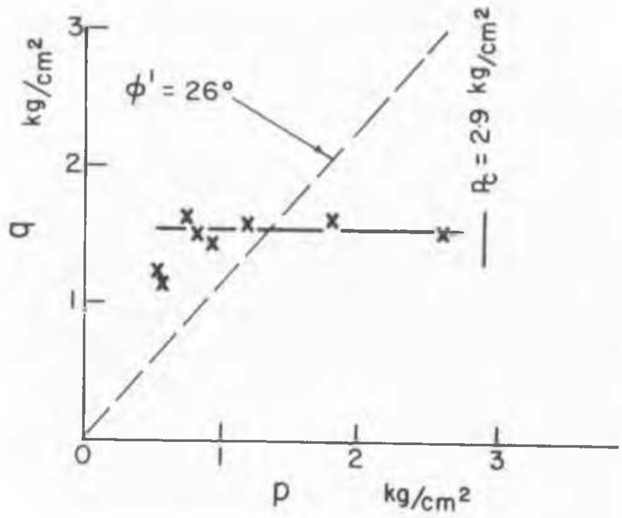

Figure 3 - The compressive strength of Leda clay.

Compressive Strength - Effective Stress Relationships

The variation of cementation bond strength with effective stress is of considerable significance when attempting to interpret the in-situ behaviour of a brittle soil. A number of consolidated triaxial specimens of Leda clay were tested at varying effective cell pressures, and the bond strength was obtained from the initial peak in stress-strain curves of the type shown in Figure 1. The results from these tests are presented in Figure 3, in which the stress difference ($q = \sigma_1 - \sigma_3$) has been plotted against

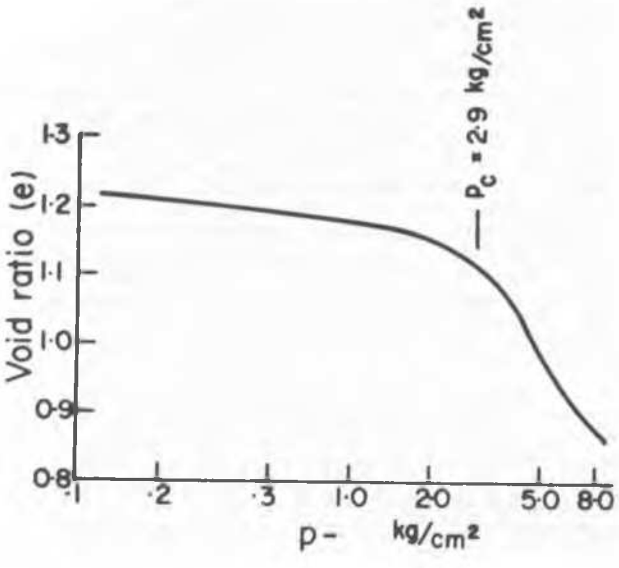

Figure 4 - The compression curve for Leda clay illustrating a high apparent preconsolidation pressure.

the mean effective stress at the peak point ($p = \frac{1}{3}(\sigma_1' + 2\sigma_3')$).

The data of Figure 3 show clearly that, apart from a slight reduction at the lowest stresses, the bond strength (1.55 kg/cm^2) is independent of the magnitude of the effective normal stress. The horizontal strength envelope is, however, restricted in pressure range, since at high consolidation pressures the cementation can be destroyed before the shear test is begun. In this respect, the compression curve is of significance, and has been reproduced in Figure 4. The apparent preconsolidation pressure is 2.9 kg/cm^2; this pressure is a measure of the effective normal stress at which bond breakdown commences in an isotropic consolidation test. Thus the horizontal strength envelope in Figure 3 cannot extend beyond the value of p_c equal to 2.9 kg/cm^2. As well as the peak bond strengths plotted in Figure 3, a second peak deviator stress is often obtained at large strains (e.g. sample LE2 in Figure 1). A similar (single) peak at large strains is also observed where high consolidation pressures are used. Such a peak may be referred to as an 'unstructured' strength, since it is associated with a complete breakdown of the cemented soil structure; the 'unstructured' strength envelope is straight and passes through the origin of Figure 3, defining an effective strength parameter ϕ'. From a limited number of measurements, ϕ' was found to be approximately 26° for Leda clay.

The strength of naturally cemented clays, as measured in consolidated triaxial compression tests, cannot in general be adequately represented by classical shear strength parameters. The soils exhibit a horizontal bond strength envelope over a wide pressure range, as well as a conventional 'unstructured' effective stress parameter ϕ'. There is no clearly defined gradation between the two parts of the overall failure envelope, and the choice of a strength to be used in design calculations is likely to depend on the particular field problem being considered.

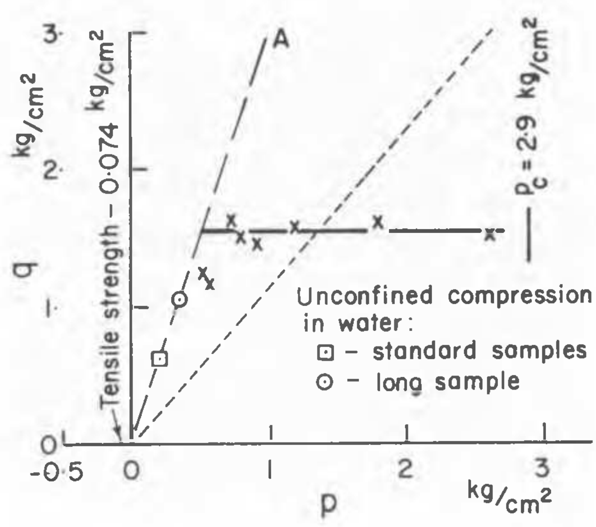

Figure 5 - A comparison of the results of indirect tension tests and unconfined compression tests in water with the compressive strength of Leda clay.

Tensile Strength and the Full Failure Envelope

Further evidence concerning the strength of Leda clay can be obtained from indirect tension tests and from unconfined compression tests in both water and air. Strength results from the first two types of tests were scattered to a degree which is not in agreement with the consistent behaviour observed in Figure 2. The tensile strength of Leda clay was measured as 0.074 kg/cm^2 ($\pm$ .012 kg/cm^2) in four tests, while the compressive strength in water was q = 0.61 kg/cm^2 ($\pm$ 0.14 kg/cm^2) in five tests; all nine of these tests exhibited an axial splitting mode of failure. The results have been presented on a $q - p$ plot in Figure 5, together with Leda clay strength data already shown in Figure 3. It is immediately observed that the unconfined (in water) and tensile strengths are considerably less than might be expected from the horizontal bond strength envelope.

From visual observation in both field and laboratory, and from the behaviour of some specimens when soaked in water for long periods of time, the authors have concluded that fissuring is an important feature of some cemented soils. Such fissures may be well spaced in the field (6 to 8 inches apart) or may be finely spaced in small laboratory specimens, as is revealed by patterns of weathering in samples given access to the laboratory environment. Whenever a tensile mode of failure occurs, the number and spacing of such fissures control the measured strength. It is considered that these factors explain the scatter of results observed in soaked unconfined compression and indirect tension tests, and the fact that all strengths measured in these particular tests are lower than the strengths measured in consolidated triaxial tests, in which a shear plane or bulging type of failure occurs.

Further discussion of the unconfined compression test in water is clarified when the stress conditions in an ideally elastic triaxial specimen are considered (Balla 1960). The frictional restraint caused by the loading platens theoretically induces radial and tangential tensile stresses in the body of the sample which are a function of the applied vertical stress. What is nominally a compression test may in fact simply be another indirect measure of the tensile strength of the soil; this conclusion is supported by the axial splitting failures observed in all five unconfined tests reported above. In general, it must be concluded that this particular test is unacceptable as a method of obtaining the compressive strength of a cemented clay.

In an attempt to obtain a valid measure of the unconfined compressive strength in water, one test was performed on a Leda clay specimen of dimensions 6" x 1½" diameter. Failure in this test was observed as a combination of axial splitting at the sample base, and planar shear failure towards the centre of the specimen. The strength of $q = 1.06$ kg/cm^2 was considerably higher than results obtained in conventional tests, and more closely approximated to the horizontal bond strength envelope (Figure 5). In specialized tests of this type, it appears that a compressive failure mechanism may possibly develop, thus permitting an acceptable strength measurement to be made.

The unconfined compression tests performed in air indicated strengths which agreed with the consolidated triaxial test results. A mean strength of $q = 1.74$ kg/cm^2 ($\pm$ 0.37 kg/cm^2) was measured in three tests with an inclined failure plane being observed. In these tests, there exists within each sample a negative pore water pressure, whose magnitude is a function of the sampling process. The sample is thus subjected to an (unknown) effective confining pressure, and agreement with the horizontal envelope of Figure 5 is obtained, although a significant scatter of data is again present.

The test results on which the above discussion is based appear to be supported by data presented by Crawford (1963) and Conlon (1966). Crawford tested a Leda clay from the Ottawa area, and reported soaked unconfined compression strengths significantly lower than corresponding tests performed in air. His observation of failure planes in the two tests appears to be consistent with the authors' evidence.

Conlon tested a cemented clay from Northern Quebec and reported soaked compressive strengths which were one-half of strengths measured on unsoaked specimens, whether confined or unconfined. Conlon also measured tensile strengths of 2.4, 2.5 and 17.5 lb/in^2 in three tests. It is suggested that the latter test was performed on a non-fissured sample, and that the former strengths were not compatible with the high compressive bond strength (55 lb/in^2) due to the influence of fissuring in the tension test. For this reason, a single theory attempting to relate strength behaviour in compressive and tensile stress regions (Townsend 1967) appears to be invalidated by the different structural behaviour of the soil in these zones.

In summary, the data presented in Figure 5 defines the full experimental strength envelope for Leda clay. Over the stress range of p lying between 0.5 kg/cm^2 and 3 kg/cm^2, a horizontal bond strength envelope is obtained, with an eventual gradation at high pressures into the 'unstructured' envelope represented by the parameter ϕ'. Compressive strength measurement for values of $p < 0.5$ kg/cm^2 are limited by a straight line (OA) through the origin (of slope artan 3) which contails all unconfined compression test data with zero lateral effective stress.

True experimental compressive strengths cannot be determined in this test due to the tensile mechanism of failure, which may also affect data from consolidated triaxial compression tests with very low confining pressures. Such measured strengths are influenced greatly by the testing method, and should in practice be rejected. It remains for future work to determine whether true compressive failures can be obtained in either field or laboratory for stress states lying to the left of OA in Figure 5.

Behaviour of Mattagami and Labrador Clays

The varved nature of Mattagami clay was incorporated in the analysis of test data, as the effective stresses were calculated on the measured failure plane. For all reported tests on this clay, the failure plane and plane of varving coincided. In general, the observed results from Mattagami clay confirmed in all respects the behaviour reported for Leda clay. The stress-strain curves were essentially linear until the bond strength was reached (as in Figure 1) and this cementation strength was constant ($q = 0.65$ kg/cm^2) up to a normal stress $p = 1.0$ kg/cm^2, which compares favourably with the measured apparent preconsolidation pressure of 1.1 kg/cm^2. At high stresses an 'unstructured' strength parameter ϕ' of 29° was measured. Both indirect tension and unconfined compression tests in water resulted in a tensile mode of failure, and these strengths were considered to be influenced by fissuring as discussed previously for comparable tests on Leda clay.

The third cemented soil, Labrador clay, demonstrated all of the characteristics of the other two soils with one important exception. The bond strength determined in consolidated triaxial tests was not constant over the full stress range. An approximately constant strength of $q = 2.8$ kg/cm^2 was determined for p varying from 2.7 kg/cm^2 up to the apparent preconsolidation pressure of 3.7 kg/cm^2. At low stresses, however, the bond strength showed a significant decrease with decreasing effective normal stress. Tests performed on a similar Labrador clay by Kenney (1966) confirm the author's data. The reasons for the sloped bond strength envelope are the subject of current study; however the high liquidity index of 2.0 precludes any possibility that this is simply a result of overconsolidation. An 'unstructured' strength parameter ϕ' of 31° was also determined for the clay.

Design Considerations

The findings reported in this Paper have significant implications in the design of foundations and the stability of slopes. In many such problems, the soil is likely to be subjected to in-situ stresses which are not in excess of the apparent preconsolidation pressure; thus the concept of an elastic material with a strength independent of consolidation pressure is likely to be appropriate. In view of the post-peak instability of the stress-strain curve at low confining pressures, it is suggested that elastic design procedures are likely to be valid for naturally cemented soils i.e. nowhere should the calculated (by elastic theory) stresses exceed the yield point (peak strength). Whether such an approach would result in an excessively conservative design remains the subject of further study; however it appears inconsistent to apply a conventional (rigid-plastic) stability analysis, which is an upper bound solution, to a soil exhibiting work-softening behaviour. Were such an application made, the large strain (unstructured) strength would appear to be appropriate. In short, the problems of satisfying stress-strain compatibility in the post-peak region suggest that elastic design methods are required when the cementation bond strength is not exceeded.

Conclusions

Results from a variety of tests on three cemented soils have been interpreted in terms of a generally consistent behaviour pattern. The cementation bond strength was not simply a function of effective stress as in classical shear strength theory; for two of the clays tested the bond strength proved to be constant over a wide range of effective normal stress. Each of the soils exhibited an 'unstructured' effective stress failure parameter once the breakdown of cementation bond had been achieved.

Any assessment of the degree of cementation by measurement of the tensile strength was marred by the presence of fissuring, which controls the failure mechanism in cases where a tensile stress system is developed in the soil. This factor, together with the mechanical properties of the bond under compressive loading, are likely to influence overall geotechnical design in many field problems.

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