

Influence of Clay Composition and System Chemistry on Residual Strength of Saturated Remoulded Clays

by

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Introduction

THERE is little doubt that in recent years an appreciation of the nature and significance of residual strength constitutes one of the most important developments in understanding the shear strength of clays. From practical importance, it has become increasingly evident during recent years that the stability of slopes is governed largely by residual strength of natural clays. While the concept is relevant to all clays it is of particular significance for stiff natural clays where the drop in shearing resistance from peak to residual states is often large. An assessment of the residual strength of clay is necessary in the rational design when dealing with materials subjected to previous shear displacements. It also serves as a useful bound for any design. An investigation that considers the role of macro-and micro-structure along with the combined influence of compositional and environmental factors would enable to understand associated mechanisms of shear strength mobilization at large deformations.

Review of Past Work

Detailed examination of the several investigations of the recent past on residual strength shows the possibility of identifying the following three aspects of study :

- (i) Testing techniques to measure residual strength.
- (ii) Investigations that consider primarily the influence of geometrical features.
- (iii) Laboratory studies on remoulded clays under controlled conditions to recognize the influence of compositional and environmental factors on residual strength of clays.

Several of the laboratory investigations employed any one of the following testing facilities :

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- (i) Multistage reversal direct shear box tests (Bishop and Little 1967, Skempton & Petley 1967, Marsland & Buttler 1967, Cullen and Donald 1971, James 1971).
- (ii) Triaxial compression tests with or without precut planes with modifications to reduce horizontal thrust (Bishop, Webb & Lewin 1965, Chandler 1966, Webb 1969).
- (iii) Principally because of the possibility of shearing with no change in the area of cross-section of the shear plane through an uninterrupted displacement of any magnitude a new ring shear apparatus was designed by Bishop et al (1971) for measurement of residual strength of undisturbed and remoulded clays.

It is inevitable that considerable differences between values measured by the above techniques would arise due to the plane of failure along which the residual shearing resistance is measured and the magnitude to which the soil samples could be deformed.

Depositional processes and later diagenetic or tectonic processes can give rise to geomechanical (macro-structural) features such as fissures, bedding planes and slickensides. In arriving at the correlations between the residual strength as measured in the laboratory and strength mobilized along several slips the influence of geomechanical features need be considered. Directional effects along or across bedding planes appear to control the path of strain. Investigations by Skempton and Delory (1957), Gould (1960), Skempton (1964), Ringheim (1964), Bishop, Webb and Lewing (1965), Bjerrum (1966), Hutchison (1967) and James (1971) provide sufficient evidence regarding the effects of geomechanical features on residual strength. In the case of sensitive clays it is likely that the magnitude of residual strength would be partly influenced by the microstructure.

There is a group of investigations Skempton (1964), Morgenstern & Tchalenko (1967), Kenney (1967), Smart (1970), and Foster and De (1971) which attempt to examine the basic mechanisms involved in the shearing resistance mobilized at large deformations. Fundamental insight into nature of residual strength is obtained from the important contribution by Kenney (1967) who presents the results of direct shear tests on several natural soils, pure minerals and mineral mixtures. Details of mineralogy are reported and where possible the composition of the pore fluid was controlled. In order to understand the basic mechanisms mostly clays remoulded under controlled conditions are employed. The possibility of geomechanical features masking the influence of microstructure is thus eliminated. On certain cases the data has been interpreted from clay fabric conditions (particle orientation, Kink band phenomena), and at times (Morgenstern & Tchalenko (1967), Foster & De (1971) supporting evidence, by direct methods of fabric identification has also been provided.

Comparatively the investigations pertaining to the above phase are only few. It is attempted in this investigation to discuss the various basic considerations regarding the nature of fabric as influenced by compositional and environmental factors and the subsequent changes that would result due to large deformations. The experimental aspect of the study confines to examine the influence of the following factors on the residual strength :

- (a) clay composition,
- (b) system chemistry,

- (c) stress history (normally and over-consolidated), and
- (d) undrained and drained test conditions.

Influence of geomechanical features are outside the scope of study and experimental work would confine to saturated clays remoulded under controlled conditions.

Basic Considerations

The shear strength of a soil, under specified test conditions, is the maximum shear stress it can withstand. Many of the recent studies on the basic mechanisms of the shear strength mobilization recognize the physical manifestation of complex physico-chemical interactions between particles. It is difficult to visualize the manner in which the bonds between the different units are disrupted and reformed and the resultant changes in reorientation unless the nature of clay-water interaction as well as the mechanical particle to particle interactions are considered. Understanding of basic mechanisms would further gets complicated due to the nature of the system chemistry. The physical constitution of the soil system as expressed by the spatial arrangement of solid particles and associated voids constitute the fabric of soil. The mechanisms by which and through which different soil fabrics are realized is an expression of the combined influence of compositional and environmental factors. Composition, i.e., clay and non-clay mineral type, size, shape and surface area adsorbed cations, pore fluid composition establishes the potential for any given property to assume a particular value whereas the actual magnitude of a property is governed by environmental factors, like initial mode of stress application and lateral constraints, time and temperature. In a system in which the bonding forces dominate over disruptive forces, the tendency for flocculation is marked (Nagaraj & Narasimha Rao 1972). This results in the formation of clay clusters or aggregates with the size and nature of physico-chemical environment. Cementation bonds could also exist at these particle contacts and between clusters depending on the nature of reaction products. This enables to recognize different domains having distinctly different or identical characteristics. On the contrary such clear domains would not develop in such systems where the disruptive force surpass the bonding force. The boundary between domains often diffuse and indistinct, thus the resultant fabric is identified as turbostatic.

Shearing tends to slide and reorient the particles parallel to one another to the minimum potential energy condition. Earlier to reaching this stage during the initial stages of shearing the threshold shear strength mobilized would be partly influenced by interference effects. With the inducement of large shearing strains oriented matrix reaches a stable configuration. Particularly in the cases where the physico-chemical environment has actuated the formation of clay aggregates, packet structures rearrangements and reorientation could take place between fabric elements without any significant distortion within the fabric elements (Yong 1971). Hence when the fabric elements behave like individual units even if the clay composition being same, the system chemistry could influence the residual strength. The magnitude to which the residual frictional parameter gets affected depends on the stability of the fabric elements formed under different physico-chemical environment. The stability of individual units depends upon the changes both due to changes in surface characteristics (interparticle forces) and cementation bonds due to reaction

products. The present experimental study is undertaken to recognize how far this deductive reasoning is valid for kaolinite and montmorillonite clays.

Experimental Work

Commercially pure kaolinite and montmorillonite clays were used in this investigation as they, by the very nature of their crystal lattice structure exhibit a wide range and diversified mechanical behaviour (Grim 1959). Different electrolytic environment formed the system chemistry of the saturated clays. Calcium hydroxide and sodium oxalate were selected as trace additives as a part of continued investigation on physico-chemical aspects of soil behaviour (Ranganatham 1961, 1965 & Nagaraj 1964, 1966, 1968). Table I shows the physical properties of soils. The percentages of additives used were in accordance with the requirements to satisfy their base exchange capacities. Changes in surface and matrix characteristics of clays are brought about by these trace additives. Adsorbed calcium cations depress the double layers inducing the tendency to form clay clusters and aggregates. Due to sodium exchangeable cations in the interstitial fluid double layers are almost fully mobilized. The double layer repulsion increases the potential energy of the system tending towards the turbostatic fabric conditions under stress history. The possible changes in the nature of both bonding and disruptive forces of both the systems are discussed in a separate paper (Nagaraj and Narasimha Rao 1972).

Sample Preparation

Saturated samples were obtained by K_0 -consolidation of clay-water-electrolyte slurry at twice the corresponding liquid limit consistency. Thorough mixing of clay-water-electrolyte were done by mechanical stirrer. Perforated brass moulds of one cubic foot capacity used to consolidate the slurry enabled all round drainage. The final consolidation pressure of 1 kg/cm^2 (1 ton/sq/ft) was reached in increments allowing sufficient time for consolidation under each load increment. The samples obtained were of adequate consistency to be handled and the samples for triaxial testing were obtained by driving thin walled brass tubing of 3.8 cm (1.5 in.) diameter and samples of 7.6 cm (3 in.) height were trimmed for use in the triaxial tests.

Testing Methods

For the experimental part of the study on residual strength of soils (i) direct shear, (ii) triaxial compression, (iii) torsion or ring shear tests have been employed by earlier investigators. It is inevitable that slight differences between the values measured by different testing techniques would arise due to lateral constraints, nature of stress distribution and the magnitude to which the soil samples could be deformed. Triaxial compression test with the method by Webb (1969) to compute normal stresses at residual stage of deformations has been adopted in the present study. In each of the individual tests deformation corresponding to residual shearing resistance was identified when the rate of change of stress difference pore water pressure/volume change approached zero. It is possible that although the residual strength obtained by several testing techniques might not be identical yet the degree of deviations might not be such as to radically affect the interpretation of test data.

TABLE I

Index Properties of Different Systems.

Soil type	System chemistry	Liquid limit %	Plastic limit %	Plasticity index %	Shrinkage limit %
1 Kaolinite clay	—	49	29	20	27
2 „	Calcium hydroxide	67	29	38	30
3 „	Sodium oxalate	31	25	6	28
4 Montmorillonite clay	—	580	85	495	12
5 „	Calcium hydroxide	222	88	134	23
6 „	Sodium oxalate	425	77	348	15

All the testing procedures correspond to the methods detailed by Bishop and Henkel (1962). In order to produce over-consolidated samples specimen already in equilibrium under a certain hydrostatic consolidation pressures were allowed to reach equilibrium under lower cell pressures. The ratio of these two consolidation pressures indicates the degree of over-consolidation. Isotropically consolidated undrained triaxial compression tests with pore water pressure measurement with back pressure technique and consolidated drained test with volume change measurement were conducted. The end restraint was minimized by the use of enlarge lubricated end platens as detailed by Rowe and Barden (1964). The ambient pressure was maintained constant during consolidation and application of stress difference during shearing by means of self-compensating mercury control. The strain rates adopted were 0.01 percent per minute for the undrained tests in all the systems and for drained tests on kaolinite clay. The corresponding rate of strain for drained tests on montmorillonite clay was 0.001 percent per minute. It took nearly three weeks to reach residual value of shearing resistance in drained tests on montmorillonite clay. The strain rates adopted were slower than required according to Blight's (1964) considerations to allow for 95 percent pore pressure equalization in undrained tests and dissipation in drained tests.

Test Results and Discussion

The geometry of the shear planes assumed is shown in Figure 1. Webb's (1969) approach is used to calculate the area of contact between wedges for the post-peak deformation from the following equation :

$$A_s = A_P \sec \alpha \left\{ i - \frac{8}{\pi} (e_R - e_P) \right\} \cot \alpha$$

where A_P = area of cross-section of the sample at peak

e_p = axial strain at peak

e_R = axial strain at residual

α = inclination of failure plane from the horizontal.

Typical Stress Strain Curves

Figures 2 through 4 show the typical stress-strain pore pressure/volume change curves corresponding to the various factors as indicated. For either of clay types it can be seen in Figures 2 and 4 that mobilization of peak strengths when calcium hydroxide formed the system chemistry, is at a faster rate beyond which the drop in strength from peak to residual is also marked. The effects of prestressing are also marked for the same system chemistry. The mobilization of higher strengths at low values of axial strain might be attributed to the strength contribution by cohesion (Lambe 1960). With the progress of straining the cohesion components due to cementation and prestressing gets deminished the drop in strength from peak to residual is marked. On the contrary no marked reduction in strength from peak to residual could be observed (Figures 2 & 4) for either of clay types when sodium oxalate formed the system chemistry. Similar trend could be observed in Figures 4 and 6 when the residual stages are reached under drained conditions of triaxial compression tests. In all the cases, irrespective of initial conditions like system chemistry, stress history and test conditions, while the samples are deformed to their respective residual level, the rate of change of pore pressure or volume change approaches zero. This was observed irrespective of the drop in the strength from peak to residual stages. It is also the reflection of the drop in strength from peak to residual due to reorientation component diminishing to zero.

Strength Envelopes

Modified Mohr-Coulomb diagrams (Figures 5 & 6) are drawn for the untreated clays and clays with different system chemistry. In each of the figures for the particular clay type Mohr-Coulomb diagrams are drawn for untreated, treated cases separately, combined data, which includes the stress history and test conditions, are used to draw the Mohr-Coulomb diagram. It could be seen that for kaolinite clay the residual frictional angle is in the range $19.5^\circ - 20.7^\circ$, for all the cases. The marked

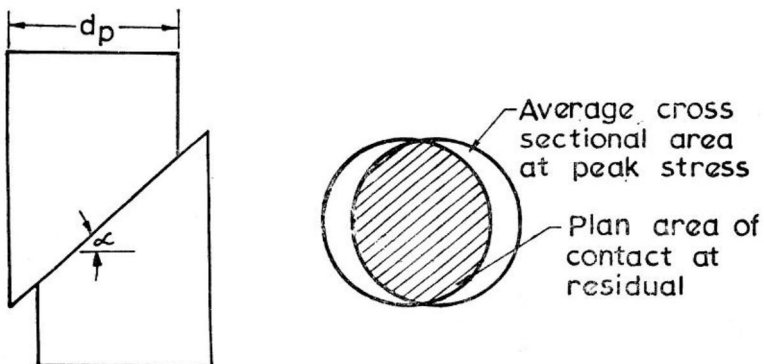


FIGURE 1 : Geometry of the shear plane.

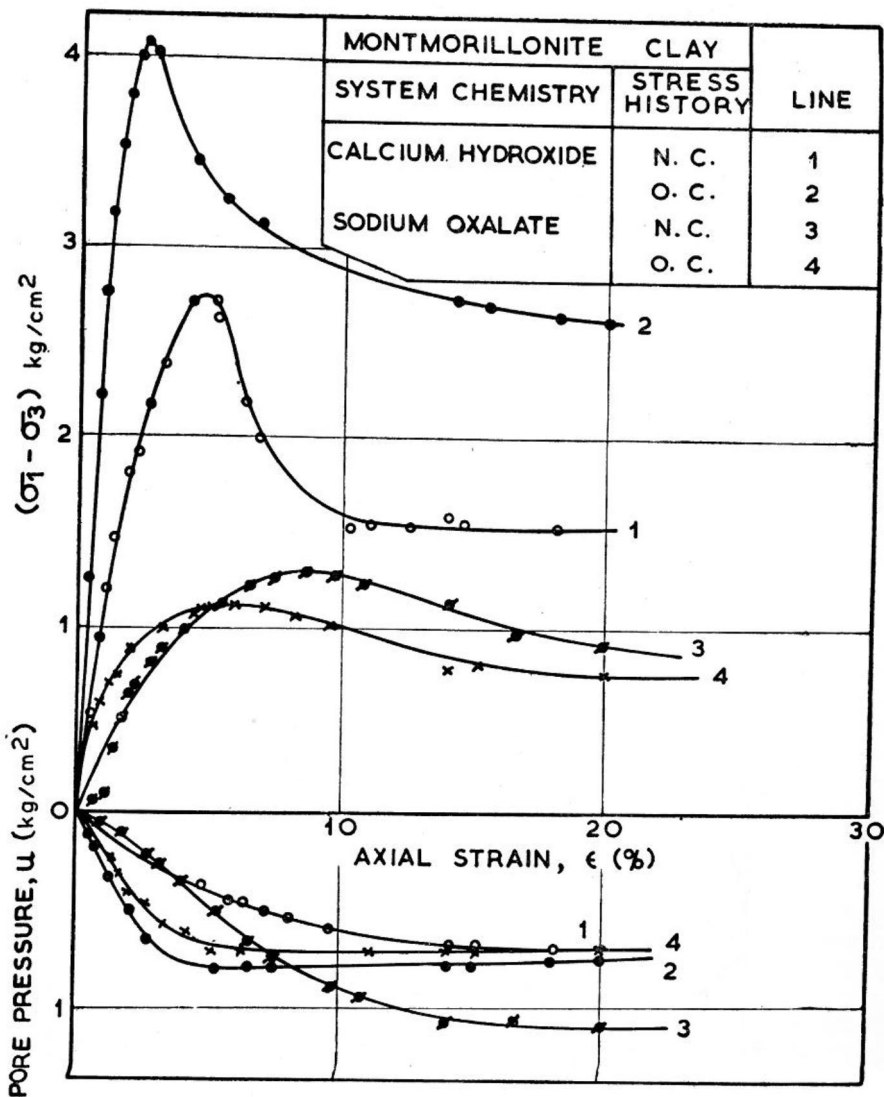


FIGURE 2: Typical stress-strain pore water pressure curves from \overline{CIU} test on montmorillonite clay, $\sigma_3 = (40 \text{ psi}) 2.81 \text{ kg/cm}^2$.

effect of system chemistry was not recognized. In the case of kaolinite clay due to lower magnitudes of charge deficiency the double layer mobilization is less. As such the system chemistry cannot markedly alter the nature of interparticle forces so as to result in formation of clay clusters or aggregates of distinctly different nature for either case of system chemistry. Hence the frictional characteristics are not likely to be markedly different. In the case of montmorillonite the effect of system chemistry could be markedly seen (Figure 5). Montmorillonite clay treated with calcium hydroxide exhibited a residual frictional angle of 22° whereas the value reduces to as low as 8° when sodium oxalate formed

the system chemistry. For montmorillonite clay the charge deficiencies are of such magnitude that double layer phenomenon in clay-water-electrolyte interactions play an important role. When calcium hydroxide formed the system chemistry, double layers get appreciably depressed so as to result in the formation of clay clusters and aggregates of appreciable size in relation to individual units. Higher value of residual frictional parameter would be due to the size and stability of fabric elements formed under such physico-chemical environment. On the contrary when the system chemistry was sodium oxalate double layers tends to fully mobilized condition. This reduces the net interparticle forces with the resultant tendency to exist in smaller fabric elements. The presence of the individual smaller units in the system is reflected in lower angles of residual frictional parameter. It could be seen in Figures 5 and 6 that the residual frictional angle is independent of the factors (stress history, initial water content, undrained and drained test conditions) considered in this study. The data indicate that cohesion intercept for the conditions considered, tends to zero for residual stage of deformation.

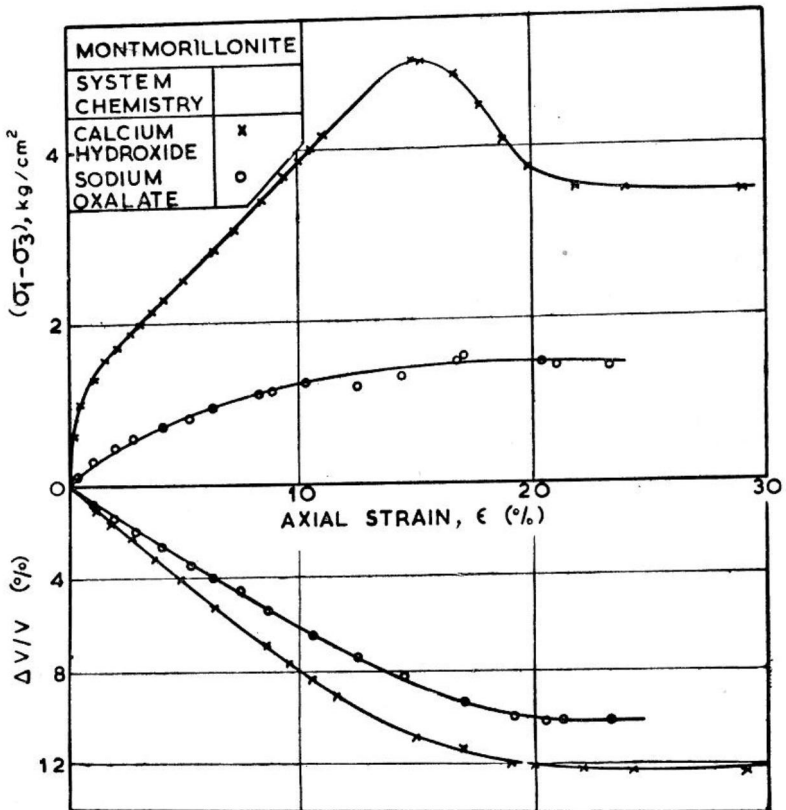


FIGURE 3: Typical stress-strain volumetric strain curves from CID tests on montmorillonite clay, $\sigma_3 = (40 \text{ psi}) 2.81 \text{ kg/cm}^2$.

Conclusions

Limited experimental data indicate that while the samples are deformed to their respective residual strength level the rate of change of

pore pressure/volume change tends to zero thereby indicating that the fabric elements (clay particles aggregates, clusters) approach stable configuration. Since the strength component due to dilatancy and reorientation diminishes to zero towards residual stage of deformation the initial fabric conditions do not influence the residual frictional parameter (ϕ'_r). This strength parameter was found to be for a clay type independent of initial water content, stress history (normally or overconsolidated) and test conditions (undrained or drained). The magnitude of residual frictional parameter was found to be primarily dependent on mineralogical

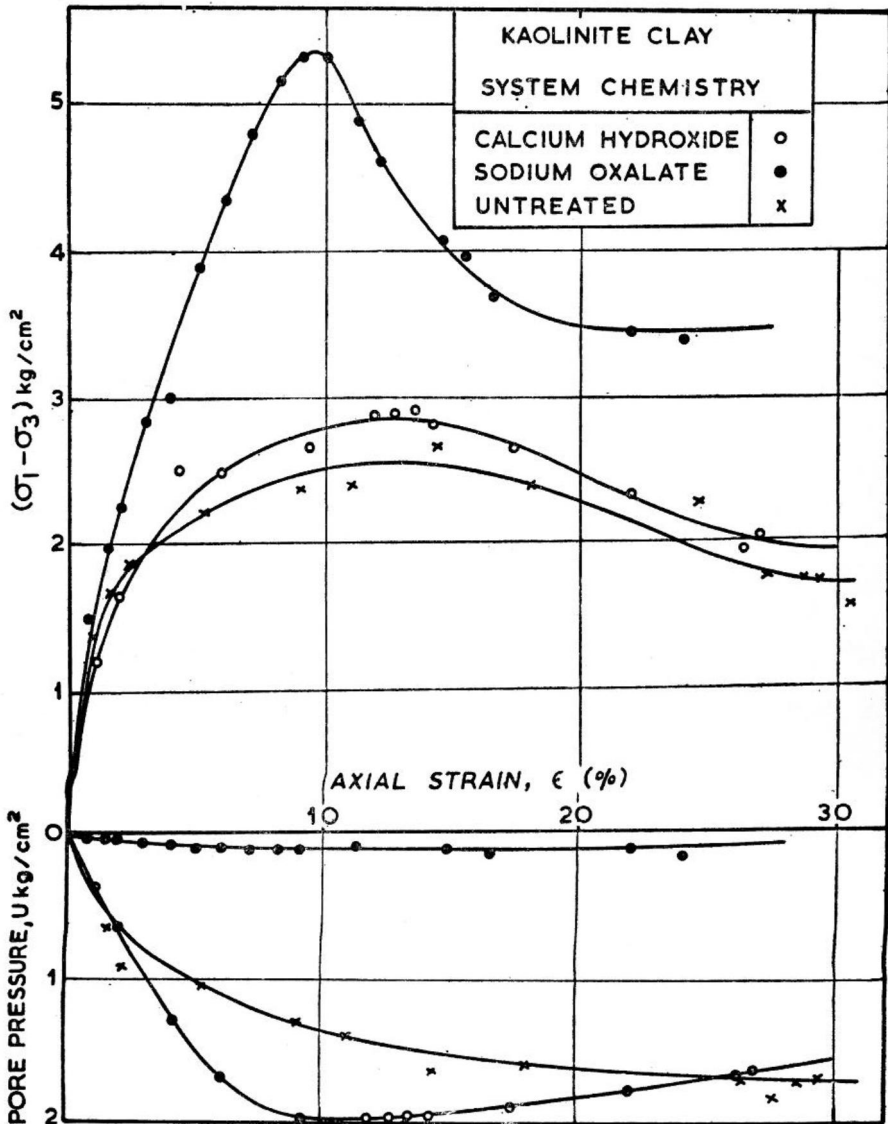


FIGURE 4: Typical stress-strain-pore pressure curves from CIU tests on kaolinite clay, $\sigma_3 = (45 \text{ psi}) 3.17 \text{ kg/cm}^2$.

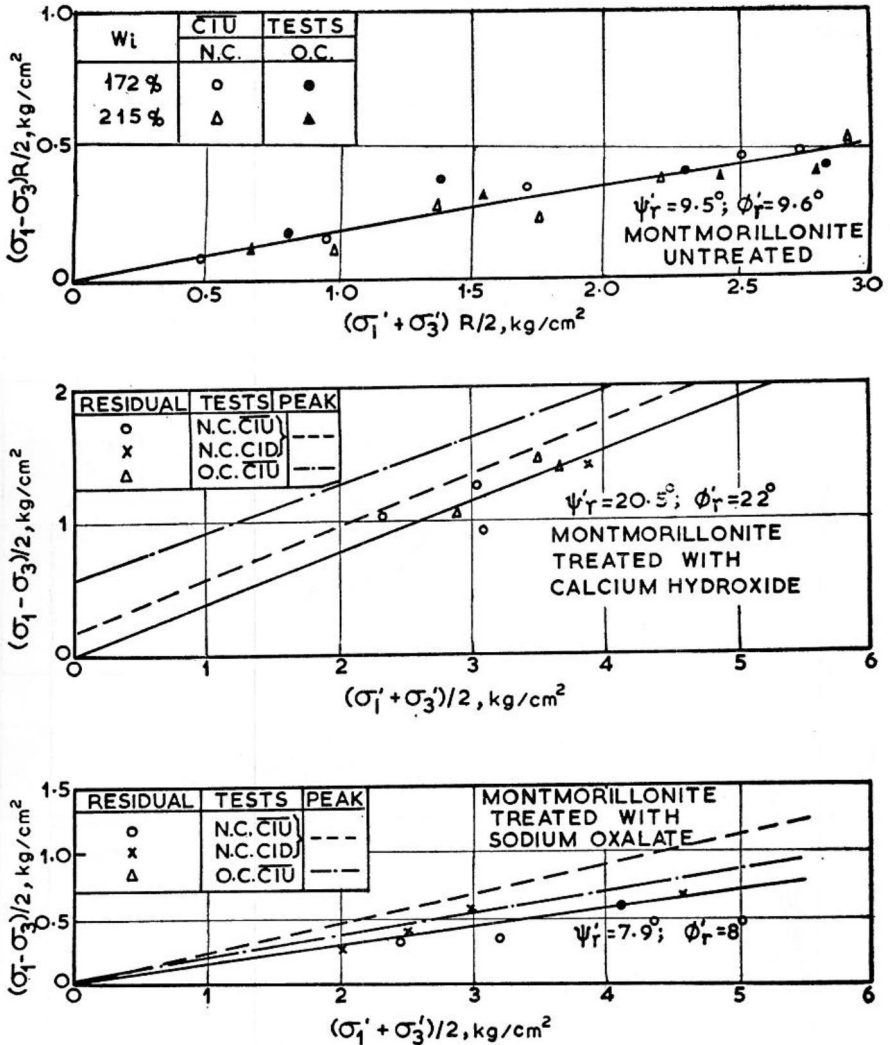


FIGURE 5: Mohr-Coulomb strength lines for montmorillonite

composition. Kaolinite clay being a massive clay mineral exhibited higher value ($\phi_r = 19.5^\circ$) than montmorillonite clay ($\phi_r = 9.6^\circ$). The influence of system chemistry was found to be marked only in the case of montmorillonite clay. The differences in the magnitude of residual frictional angle for the same clay type under different electrolytic environments might be due to the size, nature and stability of fabric elements formed under different physico-chemical environment. The exact nature of initial fabric elements and the changes induced due to deformation could only be identified by resorting to electron microscopy. The analyses of data indicate that the cohesion intercept tends to zero for residual stage of deformation irrespective of cohesive bonds due to cementation and prestressing effects. The experimental findings lead support to the

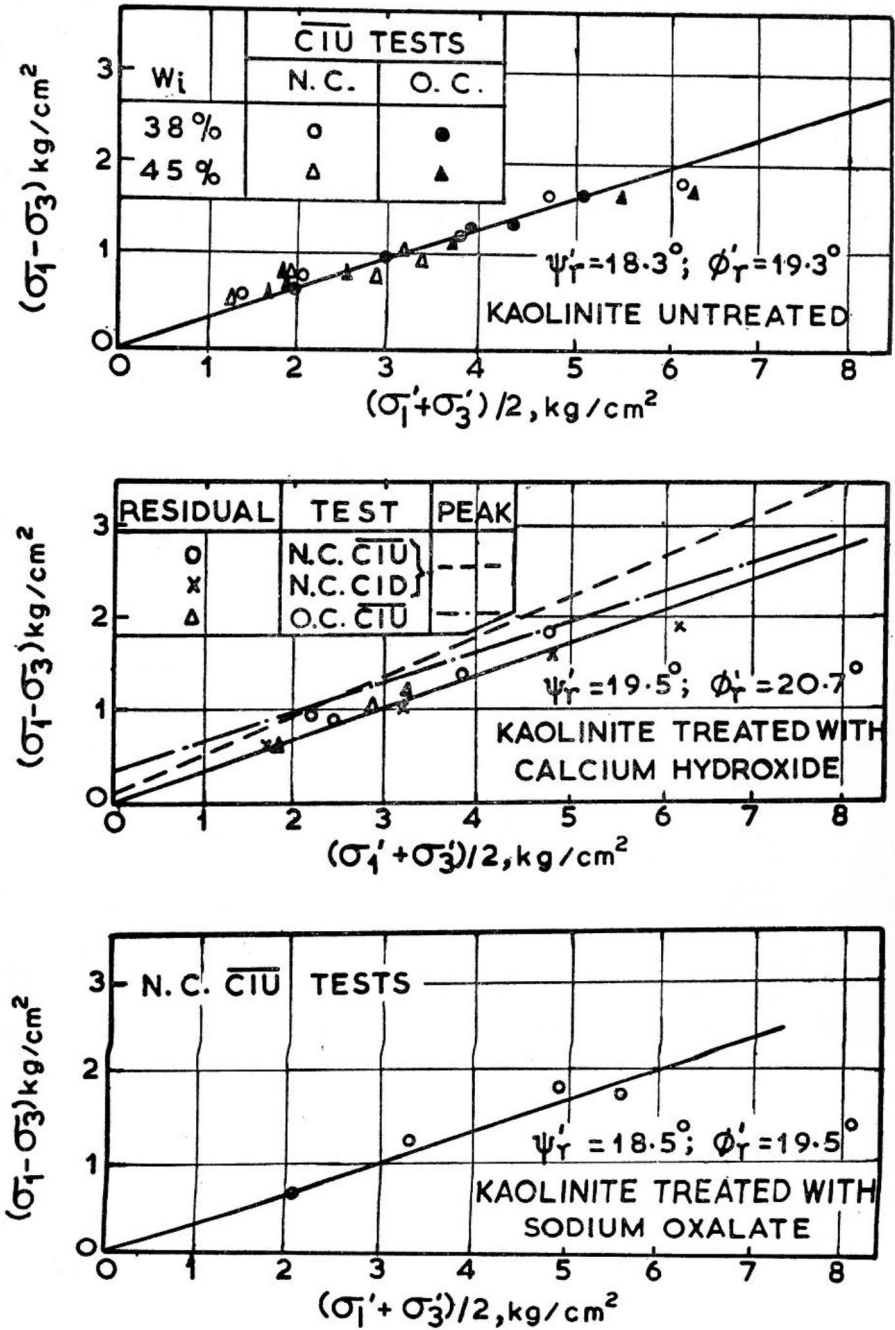


FIGURE 6: Mohr-Coulomb strength lines for kaolinite.

general considerations made on deductive reasoning. The findings of this investigation are relevant only in cases where the strength mobilization is governed by microstructure (non-fissured clays) and hence the study of influence of macrostructural features is outside the scope of present investigation.

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