Thixotropic Effects on Residual Strength of Remoulded Clays

by

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Introduction

KNOWLEDGE of shear strength at large strains is of practical importance for estimating the effects of progressive failure or previous disturbance of the soil in stability and bearing capacity problems. The soils in nature, which are quite often affected by progressive failure are over-consolidated fissured clays and shales. These soils generally contain highly active minerals such as montmorillonite and illite. The strength at large strains is referred to as residual strength which governs the behaviour of over-consolidated fissured clay slopes. The rational explanation of Skempton (1964) in his Fourth Rankine Lecture and his subsequent studies (Skempton and Petley, 1967; Skempton, 1970) have shown the importance of residual strength. Bjerrum (1967), following the explanation of Skempton (1964), has thrown more light on the progressive failure by re-emphasizing the significance of bond strength on it. The works of Skempton and Petley (1967) on samples from primary slips have shown small peak in stress-strain curves and one among the causes has been attributed to formation of certain type of bond. Hvorslev (1960) made an attempt in studying the regain effects of residual strength on Vienna clay.

The present investigation is aimed on the study of the effect of thixotropy on residual strength of remoulded normally consolidated commercially available kaolinite and bentonite clays.

Experimental Work

Testing programme consists of preparation of soil specimens using bentonite and kaolinite clays with predetermined quantities of water, consolidating them to a known degree of consolidation and testing in a direct shear test apparatus to evaluate peak and residual strength of the specimens and the residual strength being determined by adopting reversal

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shear box technique. After the residual stage was reached the samples were allowed for rest periods of known duration and sheared after completion of rest period up to a deformation of 7.62 mm.

SOIL SAMPLE

Commercially available bentonite and kaolinite clays from M/s. Industrial Minerals and Chemicals Company, Bangalore were used. Identification and physical test results are reported in Table I.

TABLE I

Identification and Physical Test Results.

Details	*Bentonite*	*Kaolinite*
Liquid Limit	400·00%	66 00%
Plastic Limit	45·75%	43·40%
Plasticity Index	354·25%	22·60%
Clay fraction ($<2\mu$)	71·00%	11·00%
Specific Gravity	2·65	2·50
Base Exchange capacity (m eg/100 gm of soil)	24·30	0·30
Classification (I.S S.)	CH	MH

PREPARATION OF SAMPLE

A known weight of air dried sample was mixed with predetermined quantity of distilled water (700 percent bentonite and 80 percent for kaolinite by weight) and thoroughly mixed. The slurry was allowed for moisture equilibrium for seven days and then placed in layers in a perforated inner mould of 10.8 cm diameter surrounded by a solid outer moulder of 15.24 cm diameter and the spaced in between the moulds being filled with clean sand. The whole assembly was placed in a water tray. Every attempt was made to remove air bubbles completely by shaking and the sample was then allowed to consolidate on its own weight for a day. Samples were consolidated to pressures of 0.3, 0.6 and 1.0 kg sq cm by doubling the load with one day duration. The specimens were trimmed and loaded in a direct shear box under normally consolidated condition and allowed for 15 hours of further saturation.

Bentonite samples were tested for different rest periods of 0, 12, 24, 48 and 96 hours after obtaining residual strength for three normal pressures. Kaolinite samples were tested for 96 hours of rest period only for three normal pressures.

TESTING PROCEDURE

The reversal shear box technique as advocated by Skempton (1964) for determination of residual strength was adopted. However, a slight modification as regards to strain rate was followed herein. The investigation of Ramiah and Raj (1971) revealed that adoption of a strain rate ratio (ratio of strain rate for first forward to subsequent forwards and reversals) of 1 : 2 practically gives accurate value of residual strength, provided a low strain rate is adopted for the first forward depending on the type of soil. Hence, during the first forward a low strain rate of 0·0127 mm/min was adopted and for subsequent forwards and reversals the strain rate was doubled to 0.0254 mm/min.

Discussion of Test Results

Based on test results, the following discussions are presented.

STRENGTH DEFORMATION BEHAVIOUR

Typical strength displacement curve of bentonite for zero test period condition for one normal pressure of 1.0 kg sq cm is presented in Figure 1. It is observed that at low consolidation pressure, the number of cycles needed to bring to residual stage is more as compared to high consolidation pressure. At low consolidation pressure the void ratio is more and at every reversal fresh soil from the top half of sample comes in and hence takes more reversals to attain the residual stage. This behaviour is less pronounced at high consolidation pressure wherein the number of cycles needed are three to four. Thus, the reduction in strength from peak to residual is fast for highly consolidated sample and similar behaviour is usually represented by over-consolidated fissured clays.

THIXOTROPIC EFFECT ON STRENGTH DEFORMATION BEHAVIOUR

Figures 2 and 3 represent strength deformation curves of bentonite and kaolinite respectively for rest periods of 96 hours for normal pressure of 0.3 kg sq cm. Similar behaviour was observed for all normal

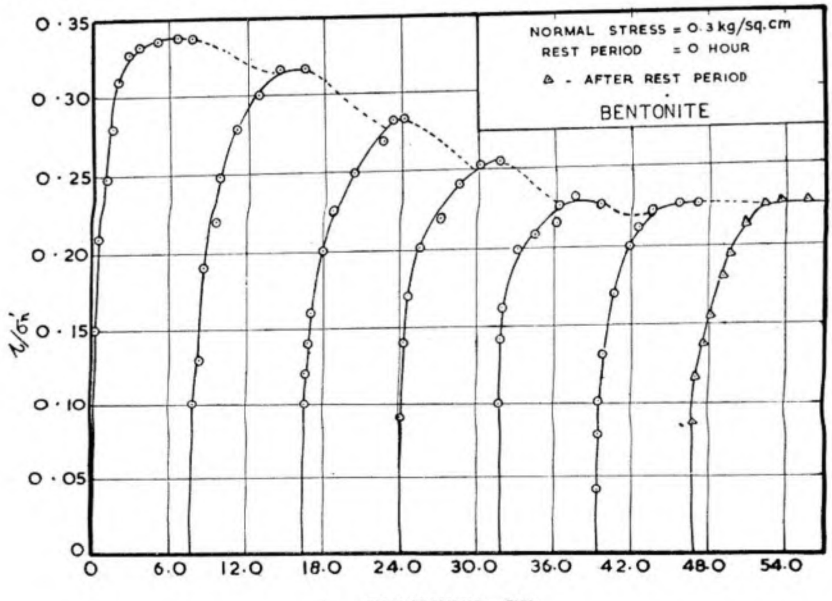

FIGURE 1 : Strength-displacement curve for 0-hour (Bentonite).

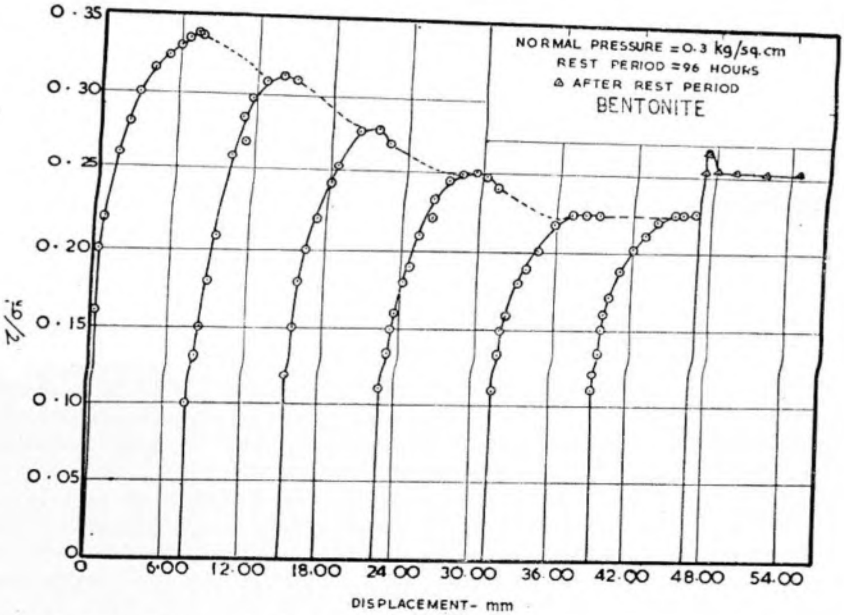

FIGURE 2 : Strength-displacement curve for 96 hours rest period (Bentonite).

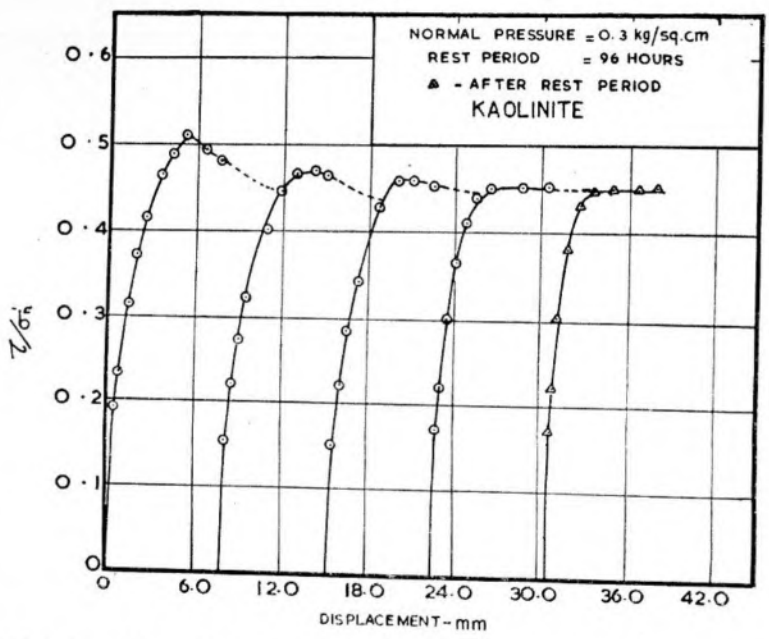

FIGURE 3 : Strength-displacement curve for 96 hours rest period (Kaolinite).

pressures and rest periods. In general, irrespective of the rest period, after the rest period (in bentonite) the strength attains its maximum value at a short duration of deformation, a behaviour generally observed for brittle materials. This behaviour has been attributed in literature as 'Stiffening or Hardening of the Soil', which is a characteristic behaviour of highly thixotropic materials such as bentonite which is rich in montmorillonite mineral. But, this behaviour was completely absent in kaolinite which is a clear example of non-thixotropic material. This implies that rate of thixotropic stiffening is extremely high in bentonite as compared to kaolinite. Moreover, it was realised by Berger and Gnaedinger (1949) that aging may lead to an increase in stiffness (as reflected by change in slope of the stress-strain curve) without any consequent increase in ultimate strength. This fact too is found to be absent in kaolinite which neither showed any increase of stiffness nor strength and thus characterising the typical behaviour of a non-thixotropic material. But, on the other hand, bentonite showed highly remarkable behaviour of thixotropic material. The test results of Skempton and Petley (1967) on field samples taken on slip surfaces showed a slight steep curve which may be attributed to the formation of certain bonds due to thixotropy which might have developed during the period since movement last occourred.

THIXOTROPIC EFFECT ON SHEAR STRENGTH

The shear strength obtained after corresponding rest periods for three normal pressures are plotted in Figure 4 for bentonite. Shear strength at zero rest period is the residual strength which is being plotted against 10 minutes for convenience. It may be noted from the graph a linear increase of shear strength with (log) rest period. Added to this, the rate of increase of strength with rest period is essentially constant irrespective of the normal pressure which is reflected by uniform slope of the lines. A similar behaviour was observed by Hvorslev (1960) for Vienna clay for a normal pressure of 2·00 kg sq cm. But, the koalinite has not shown any increase even after 96 hours of rest period.

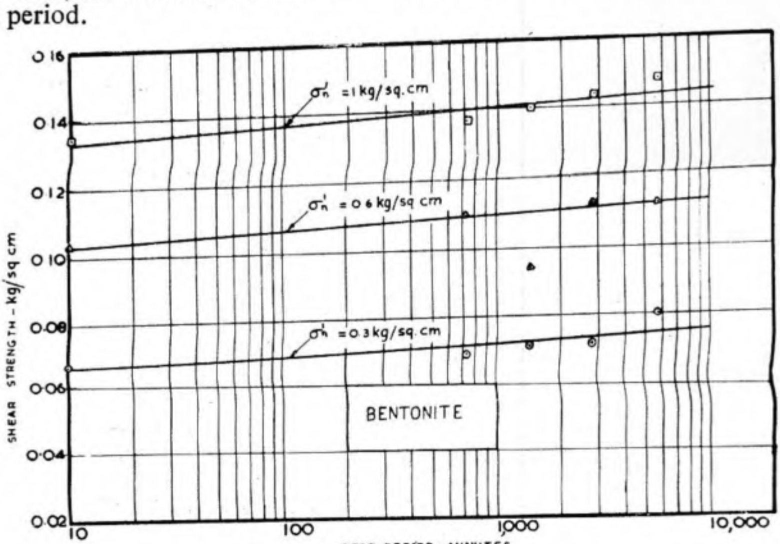

FIGURE 4 : Behaviour of shear strength with rest period (Bentonite).

Mitchell (1961) characterised the thixotropic strength gain with reference to strength at a certain strain level which was indicated by thixotropic strength ratio. Accordingly, he observed higher the strain, less the observed gain in strength. In this paper strength ratio refers to the ratio of thixotropic strength gain after rest period with that of residual strength which is nothing but the strength at zero test period. Figure 5 represents such a plot of strength ratio *Vs* log of rest period for three normal pressures. For short rest periods up to about 12 hours the increase in strength ratio observed is less but for rest periods of long duration, the increase is significant. It is found that at low normal pressures or less consolidated soils show higher increase of strength ratio than highly consolidated soil. It has also been observed that the rate of increase of strength ratio has a tendency to decrease as the consolidation pressure increases. In order to exemplify this behaviour the strength ratio is plotted against normal pressure for all rest periods in Figure 6. This graph enmarks that higher the rest period higher the strength ratio irrespective of the normal pressure. Moreover, the increase was more at low normal pressure or less consolidation pressure, e.g., it was as high as 1·20 for 0·3 kg sq cm for 96 hours rest period. A careful study of the graph indicates that at high consolidation pressure the increase of strength due to thixotropy will not be significant. In other words, when the void ratio or water content approaches plastic limit there appears to be less significance of strength increase due to thixotropy.

This fact may be further emphasized by considering the factor Δs, defined by Skempton and Petley (1967) as the difference between peak and residual strength on samples taken on 'Discontinuities'. In most of the case records given by them the value of Δs is very much less or zero. The reasons for Δs being greater than zero in tests on principal slip surfaces have been attributed to the following factors; the slips surface might

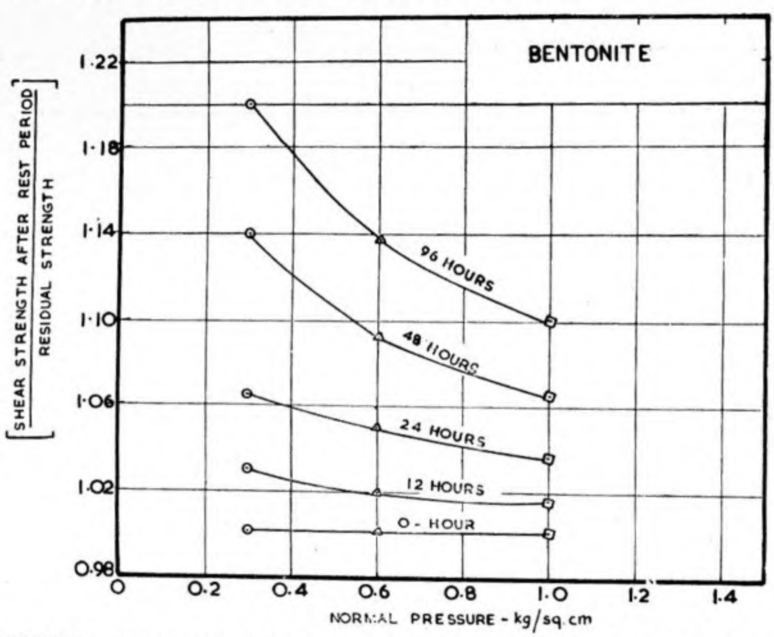

FIGURE 5 : Relationship between normal pressure and strength ratio (Bentonite).

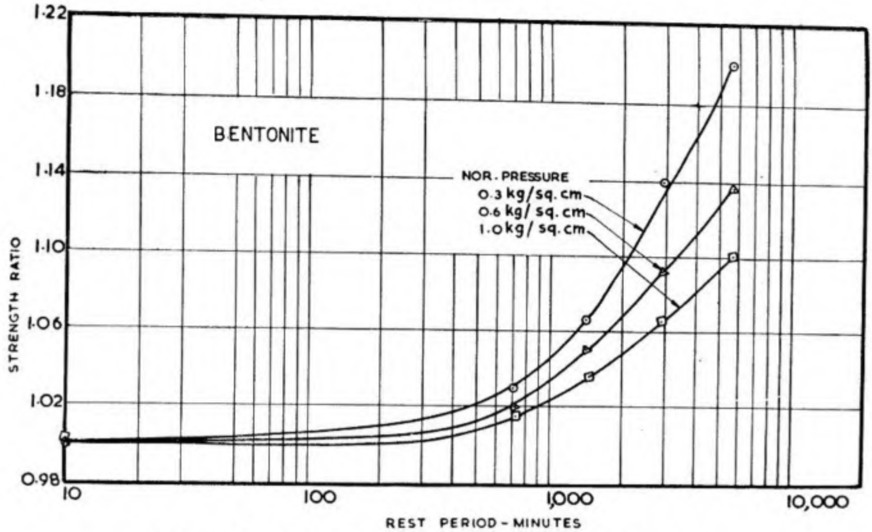

FIGURE 6 : Rest period versus strength ratio (Bentonite).

not be planer or there might be some asperities, all the clay particles might not have fully oriented or due to some bonding effect. All those clays had natural water contents at or near plastic limit. Thus, in laboratory samples also once the samples having brought to residual stage if allowed to rest may not show any significant strength increase at high consolidation pressure.

THIXOTROPIC EFFECT ON STRUCTURE

A sample subjected to continued shearing, at first reaches the peak strength and continues to decrease till a stable yielding is reached that is at residual stage (Skempton, 1964 ; Morgenstern and Tehalenko, 1967*b*). At this residual or stable yielding stage the orientation of the particles reaches a stable condition, but the force component seems to have not reached such a stable condition more particularly in a thixotropic material. But the allowance of time given after residual stage to rest for a certain period leads to an improvement over the force component since the orientation of particles has no chance to change appreciably as there was no volume change observed during the rest period. It was explained by Mitchell (1961), that most of soils when allowed for aging will try to balance the interparticles forces leading to equilibrium to a structure somewhere between complete dispersion and flocculation. In the present context the force component gets adjusted, such that the total structure reaches an equilibrium condition. Th s fact is very well reflected by the constant rate of increase in strength (Figure 4) of the samples at all normal pressures. This is the consequence of attainment of a stable and almost equal structure formation at residual stage. This confirms well with the development of continuous band of strongly oriented particles from field examples by Skempton (1964), Skempton and Petley (1967) and Morgenstern and Tchalenko (1967*a*) on tests of primary slip planes.

THIXOTROPIC EFFECT ON STRENGTH PARAMETERS

Figure 7(*a*) and (*b*) compares the residual strength envelope at zero rest period with that after 2 days and 4 days rest periods for bentonite.

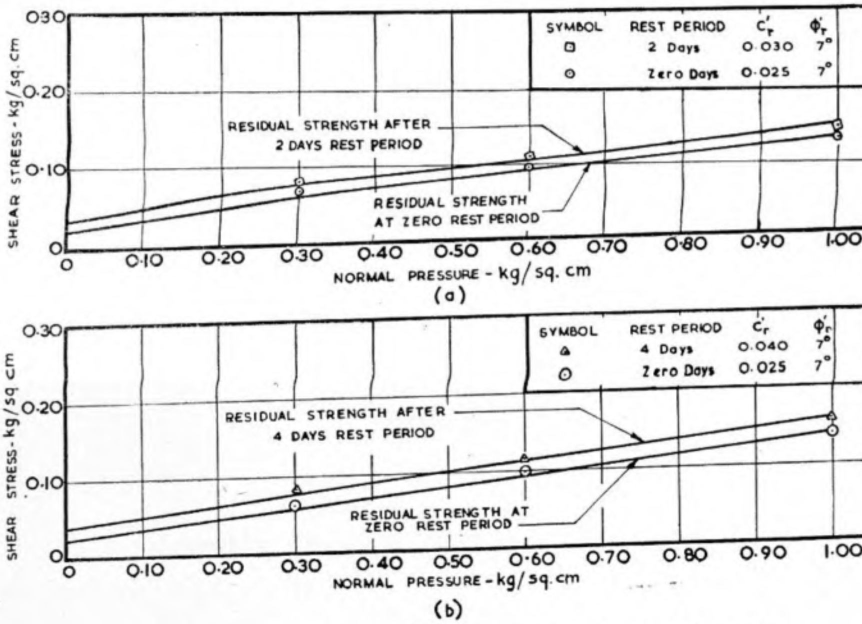

FIGURE 7 (a and b) : **Comparison of strength envelopes of bentonite.**

It is interesting to note that thixotropic effect only increases the cohesion component rather than the friction component. A similar behaviour of cohesion increase was observed by Seed and Chan (1957) on compacted soils. This is in conformity with the explanation of Day (1954) who attributed the strength gain due to changes in structure of absorbed water which is the result of increase in cohesion in this aspect. Thus, after first time landslide any increase in strength with time may be only development of cohesion, but as displacement increases, the cohesion drops down and the process hence forms a simultaneous increase and decrease of cohesion. But, the slide occurs, inpart, as the second factor, i.e., the cohesion drop, is more than the cohesion development which is usually less at plastic limit as explained earlier.

Conclusions

Based on test results and discussions the following conclusions are presented :

(1) Samples consolidated at low consolidation pressures and sheared under normally consolidated condition need more number of cycles to come to residual stage than samples at high consolidation pressures.

(2) Shear strength of a thixotropic material, bentonite, allowed to rest after residual stage gains strength linearly with (log) rest period and the rate of increase is essentially constant for all normal pressures.

(3) The strength ratio (defined as the ratio of thixotropic strength gain after rest period with residual strength at zero rest period) appears to be influenced to great extent by thixotropic strength

gain in samples consolidated and sheared at low normal pressures, whereas samples consolidated and sheared at high normal pressures (i.e., samples with water content or void ratio near plastic limit), the thixotropic strength gain does not contribute much to the strength ratio.

(4) The effect of thixotropy increases the cohesion component, but the residual friction angle remains essentially unaffected.

Acknowledgement

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