Mechanical Behavior of a Hard-Setting *Luvisol* Soil as Influenced by Soil Water and Effective Confining Stress

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ABSTRACT

A series of experiments were carried out using a triaxial system modified for unsaturated soil testing to investigate the mechanical behavior of a *luvisol* soil under varying soil water and effective confining stress levels. Mechanical properties and deviatoric stress-strain relationships of the soil were also established. The specimens were prepared under laboratory conditions where the inter-particle cementation bonds were allowed to form to their natural state. An unsaturated soil mechanics approach was used to define critical state relations for the soil. All specimens attained a critical-state under continuous shearing as a function of the level of effective confining stress. The results demonstrate that brittle / ductile behavior of unsaturated soils and their tendency to dilate / compact at failure are both controlled by soil water and effective confining stress levels. An exponential model used to fit the deviatoric stress - axial strain test data accurately predicted the trends. Soil water significantly influenced the shear strength and internal angle of friction (ϕ') and hence the mechanical behavior of the *luvisol* soil. The regression equation developed showed that ϕ' have quadratic relationships with soil water with an asymptotic surface (transitional stage). Hence, in soil tillage the transitional range (w.c. 5 - 9% d.b.) could be taken as a useful guide (soil friable state) towards understanding soil behavior upon loading when machinery and equipment traverses agricultural fields. Numerous researchers have placed great emphasis in performing tillage operations when soils are at the friable states hence minimizing compaction.

Keywords: Mechanical behavior, soil water, effective confining stress, triaxial testing, critical state, soil tillage, compaction, Kenya.

1. INTRODUCTION

The mechanical behavior of soils have been found to be highly dependent on transient properties of soil such as; water content, micro-structural state and organic matter content (Koolen and Kuipers 1983). A major part of past research effort has been devoted to establishing semi-empirical models to relate the Mohr-Coulomb shear strength parameters; cohesion (c') and internal angle of friction (ϕ'), with transient physical properties, especially water content (Alcock 1986; Mckeys 1989; Gitau 2004). Work has also been carried out to examine the influence of soil properties such as texture and water content on the brittle behavior of a given soil. Thus, the researchers felt the need to investigate the relationships between the mechanical and physical properties (through triaxial testing) of the hard-setting *luvisol* soil since the properties are known to influence soil behavior in tillage.

The micro-structural state of a soil is a presentation of the manner in which the soil particles are arranged and held together and can be defined in terms of inter-particle bonding and contact. In general the micro-structural state of a soil can be described by the extent of development of cementation bonds. Two limiting states of this arrangement can be defined and have been chosen for their ease of reproducibility under laboratory conditions (Gitau and Gumbe, 2004). The *cemented* model represents the soil with cementation bonds left intact and the *remoulded* model where cementation bonds have been physically disrupted. In a real field situation the soil could exist in conditions which are intermediate to these states but these conditions (*in-situ*) are far too complicated to be reproduced in triaxial laboratory specimens. The *cemented* model was chosen in the study since it represents conditions in a soil whereby; after being loosened when dry, soil is subsequently subjected to a series of wetting and drying cycles and then allowed to dry to ambient water status without application of external stresses. When the cementation bonds become dominant in the microstructure, the soil becomes a hard porous medium having high bulk strength (Hettiaratchi, 1988) which is a good representation of the field conditions of this type of hard-setting soil.

Thus the objectives of the study were to investigate; the mechanical behavior of the *luvisol* soil under varying soil water and effective confining stress levels and ultimately predicts soil behavior during compaction and dilation. This forms the basis of understanding the behavior of agricultural soil upon loading during compaction or loosening depending on the engineering application of the soil.

2. THEORETICAL CONSIDERATION

2.1 Critical State Theory

Over the last 40 years a fourth model of soil behavior has been established and originates from the work of Roscoe *et al.* (1958) who suggested that, within saturated remoulded clays subjected to loading that create a constant and low rate of increasing strain, there exist both a critical state line and a yield surface. Reporting on various triaxial test results the authors showed that, when subjected to this form of loading, clays would reach and pass through a failure point without collapse and then continue to suffer deformation as both the void ratio and the stress paths followed a yield surface until a critical void ratio was achieved. At this critical void ratio the values of the void ratio, the pore water pressure and the stresses within the soil mass remain constant, even with further deformations, provided that the rate of strain is not changed (Kirby 1991). This important concept has lead to the theory of critical state, an attempt to create a soil model that brings together the relationships between its shear strength and void ratio and can be applied to any type of soil (Novello and Johnston 1995).

Ultimately, the theory has been established as a research tool for several years and is now accepted for use in limit state design (Fredlund and Rahardjo 1993; Wulfsohn *et al*., 1996; Smith and Smith 1998). The theory has become increasingly popular for the analysis of mechanical behavior of soils. It unifies concepts of consolidation, compression, yielding and failure of soils into a single framework (Wulfsohn *et al.,* 1998). The concept behind this theory is that a soil undergoing shear deformation ultimately reaches a critical state; at which large shear deformation could occur indefinitely with no change in stress or plastic volumetric strain at fixed confining stresses (Mckeys 1985; Wood 1990; Liu and Carter 2001). For each soil, this concept can be defined by the relationships among the principle stress differences i.e. deviatoric stress (q), mean effective stress (p′) and specific volume (v). Hence at the critical state:

$$\frac{\partial p'}{\partial \varepsilon_s} = \frac{\partial q}{\partial \varepsilon_s} = \frac{\partial v}{\partial \varepsilon_s} = 0 \qquad \textbf{(1)}$$

Where ε_s is the deviatoric shear strain.

The conditions signifies the point at which a soil mass will yield, fail and move during a tillage operation.

2.2 Soil Behavior under Drying and Wetting Cycles

Soils when subjected to wetting and drying cycles tend to form a granular continuum which contains flaws and defects in their matrix (Hatibu and Hettiaratchi 1993). These flaws are associated with volumetric singularities such as microscopic pores or cracks, material packing inhomogeneties or microscopic voids. Such soils when eventually subjected to external loads in partially saturated conditions deform and fail in a brittle manner. It has been established that fracture and deformation in granular materials is the culmination of progressive development of micro cracks leading ultimately to slip separation along a small number of discontinuities within the soil matrix. Therefore, brittle fracture is the sudden loss of strength on certain surfaces in the soil matrix and this behavior is associated with negligible permanent deformation.

Hence, the analysis of the mechanical behavior of unsaturated soils, which have been subjected to a wetting and drying history, cannot be dealt with by plasticity theory alone. It should be noted that most agricultural and engineering operations are performed on soils that are partly saturated and brittle failure is commonplace (Medjo-Eko, 2004). The factors governing the transition from brittle to ductile behavior of soils during operations should place greater emphasis on the nature of brittle failure and the factors governing the transition from brittle to ductile behavior and vice versa.

2.3 Stress States for Unsaturated Soils

Unsaturated soils are characterized by the presence of an air phase, a water phase and an air-water interface in the voids. Because of this, it has been difficult to describe an appropriate stress state variable for unsaturated soils (Towner 1983; Hettiaratchi and O’Callaghan 1985). However in triaxial testing conditions, the complete stress state variables have been described by:

$$\begin{aligned} p' &= \frac{1}{3}\left(\sigma_{11} + \sigma_{22} + \sigma_{33}\right) \\ &= \frac{1}{3}\left(\sigma_{11} + 2\sigma_{33}\right) \end{aligned} \qquad \textbf{(2)}$$

$$q = \frac{1}{\sqrt{2}}\sqrt{\left[(\sigma_{11} \quad \sigma_{22})^2 + (\sigma_{22} \quad \sigma_{33})^2 + (\sigma_{33} \quad \sigma_{11})^2 + 6\left(\sigma_{12}{}^2 + \sigma_{23}{}^2 + \sigma_{31}{}^2\right)\right]}$$
$$= \sigma_{11} - \sigma_{33} \qquad \textbf{(3)}$$

σ_{11}, σ_{22} and σ_{33} are the principle stresses; in which σ_{11} acts axially and σ_{22} and σ_{33} are orthogonal to σ_{11}. In triaxial testing conditions; $\sigma_{22} = \sigma_{33}$.

$$v = 1 + e \qquad \textbf{(4)}$$

Where
e is the void ratio.

The variables indicates the different stress levels experienced by soils during triaxial testing aimed at simulating *in-situ* mechanical behavior of soils during tillage.

3. MATERIALS AND METHODS

3.1 Experimental Soil

The *luvisol* soil used in the experimental investigation was a sandy clay loam (73.4% sand, 22.4% clay and 4.2% silt). The index properties (liquid limit, plastic limit and plastic index) were 27.1%, 15.7% and 11.4% respectively. The soil is classified as CL according to the unified classification system. Soil samples were collected using the traverse method in a one hectare field in the semi-arid Katumani Research Station of Kenya. The depth of sampling was 0 – 40 cm (average rooting depth of the maize variety in the region) in 10 profiles and subsequently the soil was mixed thoroughly to obtain representative specimens. The soil specimens used in the triaxial tests were considered cemented since the soil was saturated with water and then dried. Hettiaratchi (1988) has given details on the laboratory preparation of cemented soil models.

3.2 Triaxial System

A digital 'tritest' model 50 was used in this experimental investigation. The system includes a cabinet mounted triaxial cell, loading attachments and a pressure control panel. The triaxial cell was designed and built by ELE International (Eastman way, UK). The design specifications were intended to accommodate some of the unique features of triaxial testing of unsaturated soils as compared with conventional triaxial testing. The cell is capable of withstanding pressures of up to 1.7 MPa. The conventional cell has three ports which are necessary for saturated soil testing but the cell had been modified (Wulfsohn *et al.*, 1998) for unsaturated soil testing by installation of an additional port–c (shaded in Figure 1) to accommodate a pore-air pressure line. A constant cell pressure of up to 800 kPa was supplied by a compressor through port-d.

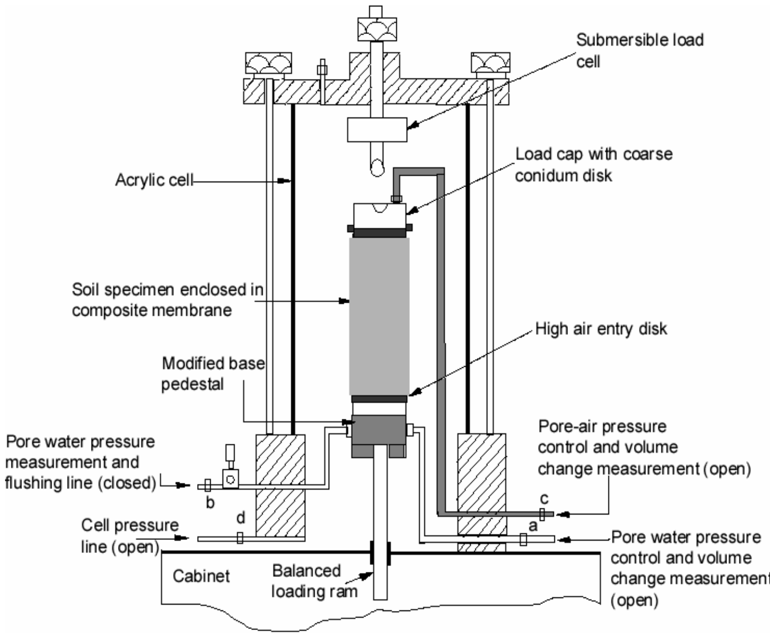

Figure 1. Schematic diagram showing the modified triaxial cell for unsaturated soil testing.

3.3 Triaxial Testing Procedures

The test subjects the soil to three compressive stresses at right angles to each other, one of the three stresses being increased until the specimen fails in shear. The triaxial tests were performed on cylindrical soil specimens subjected to all round effective confining stresses applied by pressurizing a water-filled cell. Axial stresses were applied to the specimens through a loading rod, typically in contact with the top of the specimen. The soil specimens were enclosed in rubber membranes and the ends placed between porous caps with drainage ducts to allow movement of water or air from the specimens. Consolidated drained (CD) test was applied (for deviatoric stress-strain and strength tests) to all specimens, due to the high permeability and low water holding capacity of the sandy soils. The effective confining stresses ranged between 50 and 500 kPa in increments of 50 kPa (i.e. 10 stress levels). The wide range gave good representations of testing procedures and evaluation of the critical state parameters. Three typical stages were developed for deviatoric stress - axial strain relationships depending on the soil water and mechanical behavior of the specimens i.e. stage 1 (w.c. 2.2 and 6.1 % d.b.); stage 2 (w.c. 13.7 % d.b.) and stage 3 (w.c. 15.8 % d.b.). Hence, 40 sets of experimental data were obtained from the different effective confining stresses and soil water levels. Specimens were compressed and sheared in the axial direction at a predetermined low rate of 0.25 mm/min, whereby each sample took approximately 2 hours from compression (after consolidation) through shear to failure. This allowed working at zero matrix suction, under CD tests.

3.4 Modeling

An exponential model of the form:

$$\varepsilon = C_1 \left[\exp\left(C_2\, q\right) - 1\right] \qquad \textbf{(5)}$$

was chosen to fit the test data.
Where

ε = engineering axial strain (decimal)
q = deviatoric stress (kPa)
C_1 and C_2 = model parameters (influenced by effective confining stress and soil water content).

The model parameters were determined for all the 40 sets of data using non-linear regression. Numerous researchers among them; Bailey *et al*. (1984); Bailey and Johnson (1989); Gumbe (1993), Zhang *et al*. (1998) and Gitau *et al*. (2006) have used comparable models while working on different agricultural materials with accurate predictions.

3.5 Determination of Strength Parameters

Soil strength parameters i.e. cohesion (c′) and internal angle of friction (ϕ') of the soils were determined graphically by construction of Mohr circles using levels of principal effective stresses at failure for a series of soil samples during triaxial testing and applying the Mohr-Coulomb equation:

$$\tau = c' + \sigma' \tan\phi' \qquad \textbf{(6)}$$

Where

τ = shear strength (kPa)
c' = cohesion (kPa)
σ' = effective normal stress (kPa)
ϕ' = internal angle of friction (°)

Every set values of c' and ϕ' were determined at same water content from Mohr-Coulomb equation, while varying the confining stress from 50 to 500 kPa i.e. for water contents; 2.2, 6.1, 13.7 and 15.8 % d.b. respectively. Equation 3 was used for the determination of the variable q (deviatoric stress) which has been defined for unsaturated soils. From the axial displacements, engineering axial strains (ε) were computed from the change in length during compression to the original length. Plots of deviatoric stress against axial strain were made and equation 5 used to fit the test data. Plot of strength parameter (ϕ') against soil water content was made. In all plots regression analysis were done whereby standard errors and coefficients of determination (R^2) were obtained.

4. RESULTS AND DISCUSSION

4.1 Deviatoric Stress – Axial Strain Relationships

Three distinct stages were identified for the mechanical soil behavior with increase in soil water i.e. from brittle failure through transition to ductile flow. Figures 2 and 3 illustrate, typical four-step patterns observed in stage 1 (w.c. 2.2 and 6.1% d.b.) for the changes in deviatoric stress with axial strain. A rapid rise in deviatoric stress over a short axial strain range was quickly followed by a narrow range constant rate change in deviatoric stress with axial strain followed by an asymptotic value, the critical state. The fourth step shows a decline in deviatoric stress followed by a residual steady state deviatoric stress. An exponential model (equation 5) used to fit the deviatoric stress- axial strain test data accurately predicted the trends (Table 1) with good relationship (coefficients of determination of over 70%). Most of the specimens approached failure (critical) states at between 0.10 and 0.20 axial strain. Specimens crumbled at failure showing brittle failure. At low water and effective confining stress status, the model could not fit the data (see blank space in Table 1). Again from Figures 2 and 3 the trends for this data are different in shape from the other trends. Under this low water and stress status, suction is created and the soil crumbles since it exists as a loose granular material with minimal forces holding the soil particles together. Otherwise, the model fitted the other data adequately. Similar findings have been reported by Hatibu and Hettiaratchi (1993) and Zhang *et al.* (1998) while working on sandy clay loams and soybean respectively.

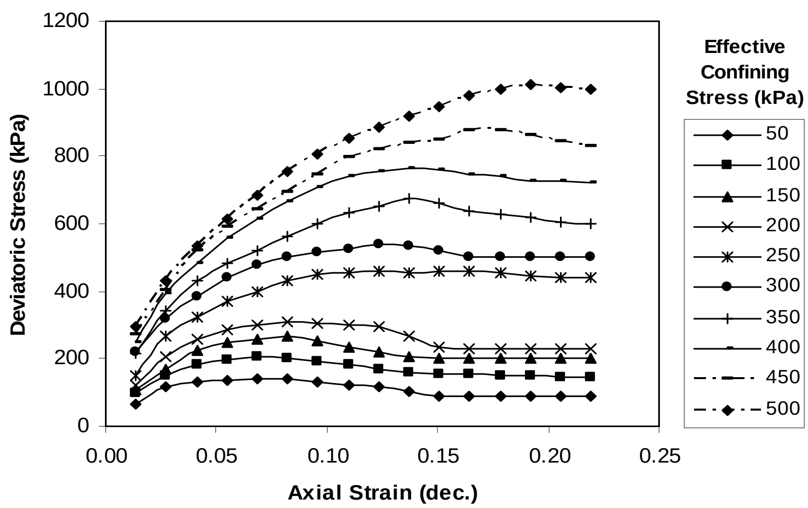

Figure 2. Variation of deviatoric stress with axial strain during brittle failure at w.c. = 2.2% under ten effective confining stresses.

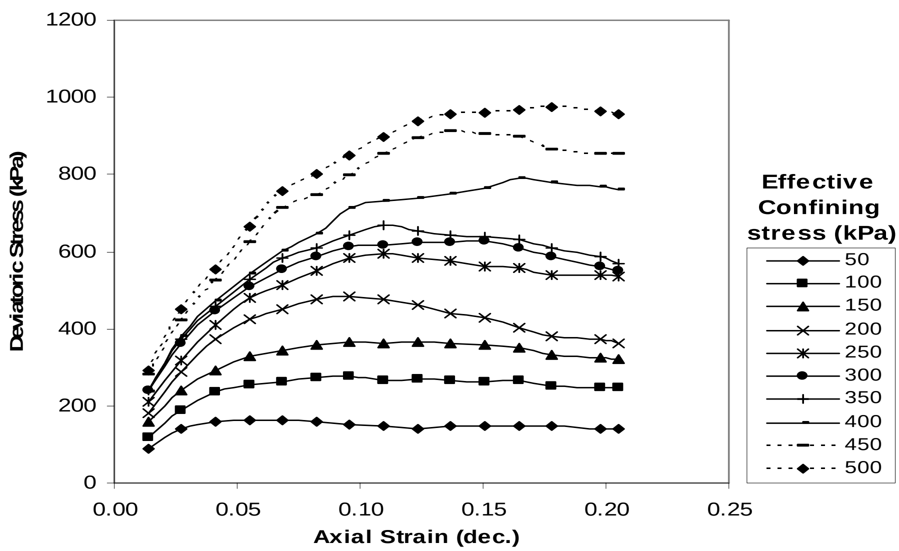

Figure 3. Variation of deviatoric stress with axial strain during brittle failure towards transition at w = 6.1% under ten effective confining stresses.

Table 1. Summary of the exponential model parameters C_1 and C_2 (standard errors in parentheses) under different water contents and effective confining stresses.

Water content (%)	Effective Confining Stress (kPa)	C_1	C_2	R^2
	50			
	100	-	-	-
	150	-	-	-
	200	-	-	-
	250	0.013 (0.0315)	0.007 (0.0069)	0.740
2.2	300	0.003 (0.0017)	0.008 (0.0014)	0.943
	350	0.002 (0.0009)	0.008 (0.0011)	0.960
	400	0.008 (0.0006)	0.004 (0.0001)	0.999
	450	0.007 (0.0017)	0.004 (0.0003)	0.987
	500	0.010 (0.0013)	0.003 (0.0001)	0.996
		0.013 (0.0008)	0.003 (0.0001)	0.999
	50	-	-	-
	100	-	-	-
	150	-	-	-
	200	0.025 (0.0420)	0.004 (0.0028)	0.744
6.1	250	0.200 (0.0371)	0.004 (0.0030)	0.759
	300	0.019 (0.0352)	0.003 (0.0028)	0.868
	350	0.028 (0.0567)	0.003 (0.0027)	0.827
	400	0.003 (0.0020)	0.005 (0.0010)	0.897
	450	0.010 (0.0100)	0.003 (0.0011)	0.761
	500	0.003 (0.0019)	0.004 (0.0006)	0.927
	50	0.018 (0.0187)	0.049 (0.0183)	0.722
	100	0.003 (0.0015)	0.030 (0.0032)	0.942
	150	0.004 (0.0015)	0.023 (0.0022)	0.957
	200	0.004 (0.0007)	0.020 (0.0009)	0.985
13.7	250	0.013 (0.0075)	0.012 (0.0023)	0.861
	300	0.004 (0.0020)	0.014 (0.0016)	0.929
	350	0.005 (0.0024)	0.012 (0.0015)	0.928
	400	0.003 (0.0015)	0.014 (0.0018)	0.916
	450	0.001 (0.0007)	0.015 (0.0018)	0.907
	500	0.001 (0.0012)	0.014 (0.0032)	0.774
	50	0.022 (0.0167)	0.026 (0.0072)	0.779
	100	0.016 (0.0036)	0.023 (0.0017)	0.955
	150	0.006 (0.0011)	0.026 (0.0012)	0.981
	200	0.005 (0.0015)	0.023 (0.0017)	0.963
15.8	250	0.001 (0.0003)	0.029 (0.0018)	0.968
	300	0.001 (0.0003)	0.027 (0.0023)	0.942
	350	0.002 (0.0010)	0.021 (0.0021)	0.923
	400	0.002 (0.0006)	0.018 (0.0010)	0.977
	450	0.004 (0.0006)	0.014 (0.0005)	0.991
	500	0.007 (0.0009)	0.012 (0.0004)	0.991

Note: The blank (-) spaces imply that at low water content and effective confining stress the model could not fit the data although it was adequate for the other data. This is clearly seen in the trends in Figures 2 and 3.

A typical three-step pattern was observed in stage 2 (w.c.13.7 % d.b.) for the changes in deviatoric stress with axial strain. From Figure 4, a rapid rise in deviatoric stress over a short axial strain range was quickly followed by a narrow range constant rate change in deviatoric stress with axial strain. The third step shows an approach to a maximum (asymptotic-critical value), a rapid decline in deviatoric stress and specimen failure. The predictive model showed high coefficient of determination (over 70%). Most of the specimens approached failure states at between 0.20 and 0.25 axial strain. Specimens bulged at failure and shear faulting was observed showing transition from brittle failure to ductile flow. Similar findings have been reported by among others Zhang *et al.* (1998) and Wang *et al.* (2001) while working on soybean and silt soils (of high sand content) respectively.

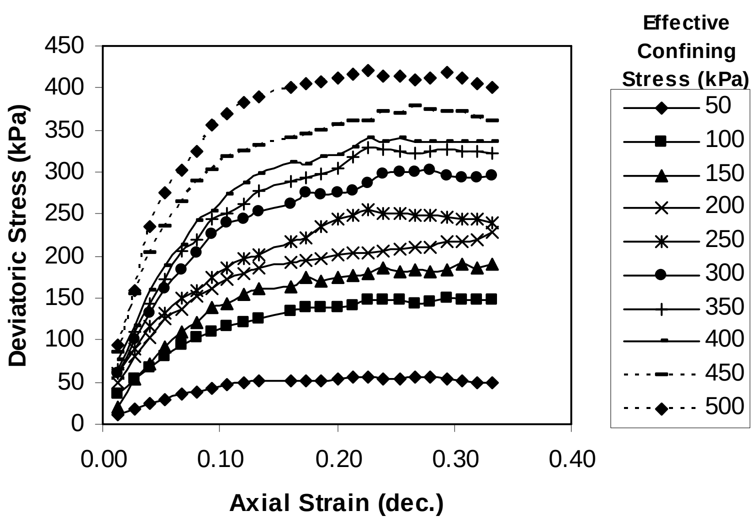

Figure 4. Variation of deviatoric stress with axial strain from the transition to ductile flow at w.c. = 13.7% under ten effective confining stresses.

Figure 5 illustrates a typical three-step pattern observed in stage 3 (w.c. 15.8% d.b.) for the changes in deviatoric stress with axial strain, but different from stage 2. A rapid rise in deviatoric stress over a short axial strain range was quickly followed by a fairly wide range constant rate of change in deviatoric stress with axial strain. These transitions indicate progressive mobilization of shear strength (maximum deviatoric stress) of specimens and attainment of critical state. The third step shows a greatly reduced, almost steady, change in deviatoric stress with axial strain. From Table 1 we observe that, the exponential model used to fit the deviatoric stress- axial strain test data accurately predicted the trends with high coefficient of determination (over 70%). Most specimens approached failure states at between 0.25 and 0.35 axial strain. Specimens bulged at failure and no distinct shear planes were observed indicating ductile flow. Similar findings have been reported by Wulfsohn *et al.* (1998) and Zhang and kushwaha (1998) while working on sandy clay loams and soybean respectively. There was significant increase in soil shear strength with increase in effective confining stress and reduction in water status in all the tests performed, since granular soil is frictional and the resistance to sliding at each contact point in sandy soils is proportional to the normal force at that contact.

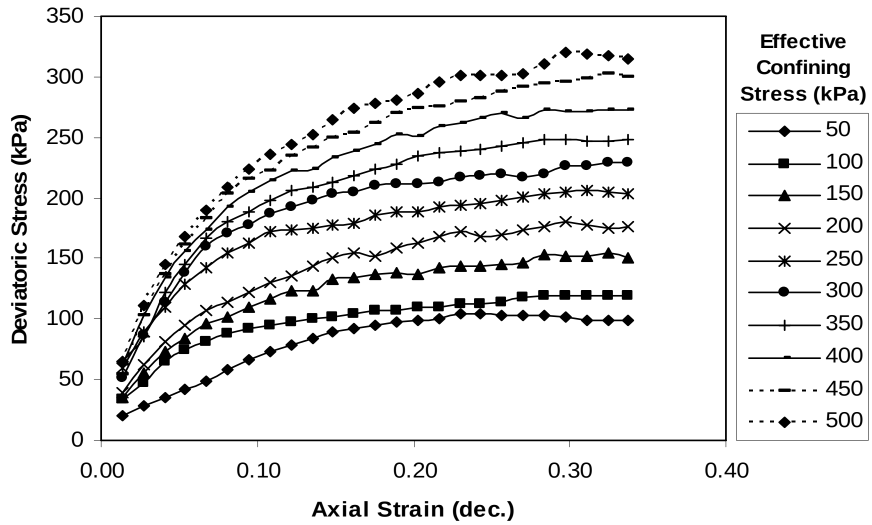

Figure 5. Variation of deviatoric stress with axial strain during ductile flow at w.c. = 15.8% under ten effective confining stresses.

For high water contents the behavior is similar to that of plastic or loose sandy soil, whereby there are no significant particle interlocking forces to be overcome and the deviatoric stress increases gradually to an ultimate value (critical state) without an asymptote. Such trends have been reported for loose soils showing a constant deviatoric stress value at varying axial strain without an asymptotic peak before failure (Peterson 1993; Wulfsohn *et al.,* 1998; Liu *et al.,* 2000 and Gitau *et al.,* 2006). Since soils vary from near liquid to very brittle materials, soil strength and soil failure are often very complex and confusing entities. Schafer and Johnson (1982) and Mamman *et al.* (2005) while investigating the changing trends in agricultural materials behavior under varying water levels reported similar findings.

The mode of failure of the *luvisol* soil from brittle through transition to ductile flow is presented in Figure 6. This mechanical property is assessed as brittle if at the end of the test the specimen shows evidence of failure by brittle-columnar (A) or faulting characteristics (B). If the specimen is observed to fail by cataclysmic (C) then the behavior is transitional. Ductile behavior was reported when the specimens showed faulting and flow as depicted by specimens D and E.

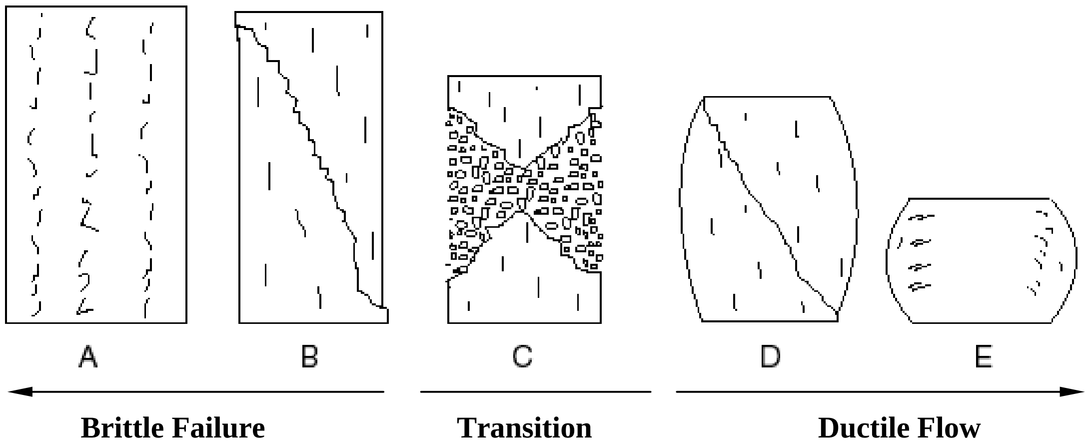

Figure 6. Classification of failure modes of specimens loaded in the modified triaxial system.

4.2 Strength Parameters

It should be appreciated that since soils are composed of mineral particles which do not interact mechanically as do metallic atoms (Mckyes 1989), a unique value of maximum shear stress (shear strength) cannot be given for a soil and hence the limit of shear resistance is composed of two components, namely cohesion and friction. The *luvisol* soil exhibited a combination of cohesive and frictional properties. Soil water was found to have a strong influence on the shear strength parameters. Similar findings have been reported by Alcock (1986) and Mckyes (1989) where shear strength increased with decrease in water content and increasing effective confining stress. Figure 7 shows that, frictional properties of this soil (for the range of water content of 2 to 6%) increased with increase in soil water (for this range) implying that the increase in soil water increased the bonding between the sandy clay loam soil particles. For the range of water content from 9 to 16% the strength parameters decreased with increase in soil water implying that higher water content reduced the bonding and frictional resistance between the soil particles. The relation between cohesion and water content was relatively low due to the low cohesive status of the *luvisol* soil tested.

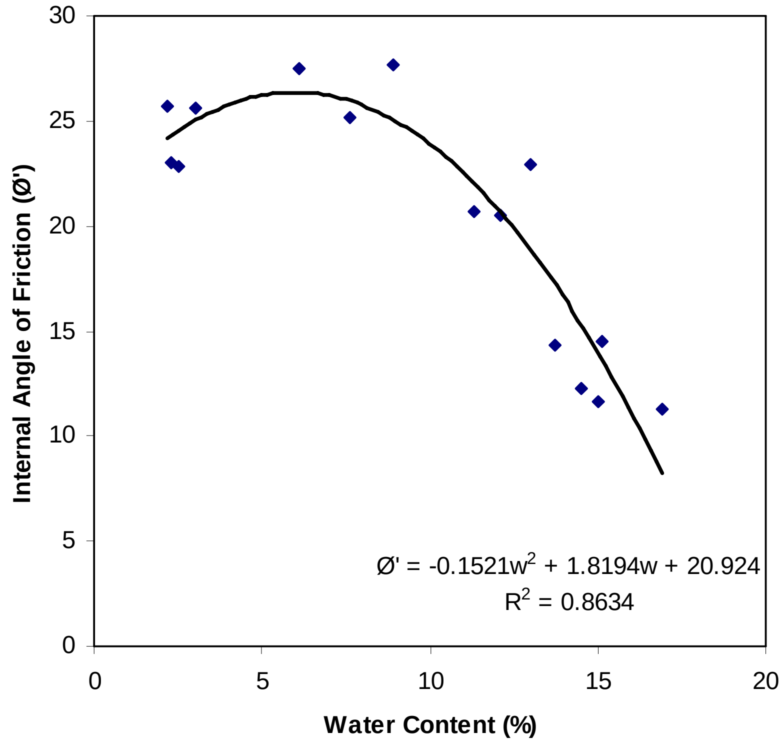

Figure 7. Variation of shear strength parameter (ϕ′) with soil water.

Soil internal angle of friction tends to increase with increasing soil water and then the curve decline with further increase in water content. The regression analysis performed showed a high coefficient of determination (R^2 = 0.86) for the angle of internal friction. The transition stage (from increase to decrease of ϕ′ with soil water) ranged between water content 5 and 9% d.b. Mckyes (1989), Girma (1989) and Raghavan *et al.* (1990) while working on different soils reported quadratic relations for this strength parameter showing an asymptotic behavior.

This shows that as the *luvisol* soil dries, the plastic state reaches a consistency at which the soil ceases to behave as a plastic and begins to break apart and crumble. The increase in shear strength with decreasing water content from the upper to the lower plastic limit is clearly seen (Figure 7). The asymptote (w.c. = 5 to 9%) represents the region of maximum soil shear strength. It is a condition frequently accepted as the upper water limit for agricultural soil working (Manuwa and Ademosun, 2007), since the soil is at its friable state and hence machinery and equipment can be introduced into the field without causing smear or compaction. At high water contents (over w.c. = 9%), clods are very weak and susceptible to deformation and aggregates produced in sandy and silt soils tend to be very weak (Alcock 1986 and Mckyes 1989).

5. CONCLUSIONS

There are two basic modes in which a soil can respond to, during loading. It can either deform plastically with pore space reduction (compaction) or it can fracture in a brittle manner with pore space increase (dilation). The triaxial compression tests presented shows that it is possible to identify the limiting conditions at which soil behavior changes from plastic flow to brittle failure, through the transition surface which is a function of soil water and effective confining stress. Soil water significantly influenced the shear strength and internal angle of friction (ϕ') and hence the mechanical behavior of the *luvisol* soil. The regression equation for the parameter ϕ' can be used to adequately predict the *luvisol* soil behavior upon loading under varying soil water levels hence predict its' behavior during compaction and dilation. The transitional range w.c. 5 – 9% d.b. represents the optimum range of soil water under which the soil is at the friable state, hence machinery and equipment can be introduced in the field with minimal structural damage to the soil.

6. ACKNOWLEDMENT

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