Dewatering and Drying Characteristics of Water Hyacinth (*Eichhornia crassipes*) Petiole. Part I. Dewatering Characteristics

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ABSTRACT

The broad objective of the study was to identify and relate the parameters that are important in dewatering of water hyacinth petiole. This involved identification of the pertinent properties that influence dewatering of water hyacinth petiole and then developing predictive empirical equations for the identified factors. Field work involved collection of samples from Nairobi dam. Experiments were carried out using a triaxial system to obtain dewatering data and behaviour of stress versus strain rate curves. Mean volume of expelled fluid during dewatering was 20.66 ml (SD = 3.5, n = 16) as at point of sample failure. Highest strain rate, at which deviatoric stress begun to be realised in the samples, was around 1.5 h^{-1}. This value was observed to decrease to strain rate below 0.75 h^{-1}, but not passing 0.5 h^{-1} mark, where strain rate remained constant as deviatoric stress increased. Mean deviatoric stresses required for expelled fluid to be realised were 20.85, 34.90, 29.75 and 28.19 kPa at confining stresses of 300, 400, 500 and 600 kPa. The developed predictive equations described dewatering characteristics of the water hyacinth petiole accurately. The significance of this study is seen in the role the results obtained will have in influencing the design of suitable dewatering equipment.

Keywords: Dewatering, deviatoric stress, fluid, hyacinth, petiole, strain rate, Kenya.

1. INTRODUCTION

Water hyacinth is botanically known as *Eichhornia crassipes* (Ogunye, 1988). According to Ogwang (2007), water hyacinth is native to South America. Barrett (1989) and Sophie (2006) have reported that the plant is thought to have originated in the Amazon basin and the extensive lakes and marshes of the Pantanal region of western Brazil. It was then widely introduced throughout North America, Asia, Australia and Africa. Schmitz *et al.* (1993) also reported that water hyacinth was introduced into the U.S. in 1884. It is noted that water hyacinth reached Africa as early as late 18th century. Between 1880 and 1980, water hyacinth appeared as an ecological nuisance in many parts of Africa. It caused a population crisis in South Africa in the 1910s, Madagascar in the 1920s, Tanzania, Uganda and Kenya in the 1930s through to the 1970s. In the 1980s and 1990s, water hyacinth bloomed heavily on Lake Victoria, the Nile, the Congo and almost all watercourses in Africa (Kitunda, 2006). Its minimum growth temperature is 12^o C (54^o F); its optimum growth temperature is 25-30^o C (77-86^o F); while its maximum growth temperature is 33-35^o C (92-95^o F) (Kasselmann, 1995). Water hyacinth is found globally in the tropics and subtropics and is considered as one of the worst weeds in the world-aquatic or terrestrial (Holm *et al.*, 1977). Figure 1 illustrates how water hyacinth can chock a water body and be an environmental nuisance and threat to eco-diversity.

Figure 1. Water Hyacinth, Eichhornia crassipes. (University of Florida, 2001). Photos stitched by ArcSoft software.

Manually cleared water hyacinth initially contain about 95.8% water, which can be reduced to only 72% after 15 days with temperatures and humidity averages of 25^{o}C and 68%, respectively (Solly, 1984). Book (1969) found out that water content of water hyacinth, derived from the mean of 82 determinations, was 93.4%. This high moisture content hinders the transportation and processing of water hyacinth as a resource (NAS, 1977). Manual control programmes have been implemented in several lakes, rivers and dams to remove the weed from the water bodies, leading to the accumulation of large mounds of water hyacinth along the water bodies. These mounds have very high moisture content and their drying and decompositions rate are too slow causing them to rot and produce noxious odour along the water bodies. The smell from the rotten heap of mechanically removed hyacinth has negative environmental impact to the surrounding. Moreover, the mounds have a negative visual impact especially for tourists. Concern over the high moisture content can be addressed so as to alleviate serious constraint to its transportation and processing for utilization.

According to Mailu *et al*. (2000), harvesting of water hyacinth must be linked to a programme of utilization for it to be justifiable. Local communities within the affected water bodies have already done this on a limited scale. A good example is Hyacinth Crafts within Winam Gulf, with assistance from the Kisumu Innovation Centre Kenya (KICK). Since 1998, KICK has developed several household items using water hyacinth fibre, as reported by Olal *et al*. (2001). Moreover, many other products can be processed from dry water hyacinth plant (Thyagarajan, 1984). Its fibre can be used as a resource to make handicrafts that provide an important source of income for the affected communities (Lindsey and Hirt, 2000). Mechanical means of dewatering have to be considered in order to lower the moisture content down to a safe level and at a rate fast enough to prevent any undesirable changes such as microbial attack and rotting. It has been reported by Olal (2005) that one way to increase the utilization of water hyacinth is to turn its apparent disadvantage into opportunity and that everyone wins when we turn this terrible weed into organic fertilizer, livestock feed or furniture. Utilization of water hyacinth is an important way of managing the weed problem and contributing to environmental management as well as creating employment and generating income for those who are most affected by it.

Water hyacinth is better suited to the production of coarse fibre products. The process was first patented in the United States in 1926 (Callahan, 1926). Research teams at Universities in Florida and California have reported failure in overcoming processing constraints. One widely experienced processing problem is the high moisture retention of fibers, rendering it unacceptable for high-speed pressing. The pulp from the petiole (stalk stem) appears better suited to the fabrication of particle board (Gopal, 1987). One alternative approach has been its incorporation into cement (reinforced) pressed boards or into waxed paper (Ghosh *et al.,* 1984).

The broad objective of the study was to identify and relate the pertinent parameters required in dewatering of water hyacinth petiole. The specific objectives were to:

1. Identify properties that influence dewatering of water hyacinth petiole.
2. Develop predictive empirical equations of the properties identified in (1) above.

Pertinent dewatering parameters were obtained from numerous mechanical research works on plant materials as cited in this study. These parameters were tabulated as shown in Table 1.

Table 1. Parameters affecting dewatering characteristics

Parameters	**Description**	**Source**
w	Expelled fluid (ml)	Mburu *et al.* (1995a); Savoie and Beauregard (1990); Sinha *et al.* (2000)
t	Time (hours)	Rotz and Sprott (1984)
q	Deviatoric stress (kPa)	Haman *et al.* (1999); Koegel and Bruhn (1972); Piggot, (1980); Zhang *et al.* (1989)
ε	Shear strain rate	Dal *et al* (1980); Li *et al.* (1989), Zhang *et al.* (1989)

2. MATERIALS AND METHODS

Field work for this study involved collection of samples from four different locations within Nairobi dam. Water hyacinth petioles were separated from the leaves and the roots in the laboratory. Triaxial testing was done on water hyacinth petioles to establish the pertinent dewatering properties and deviatoric stress-strain rate relationships. Exponential series models, that described the relationship between deviatoric stress and rate of expelled fluid were obtained. A power series model was developed for the deviatoric stress-strain rate relationship.

2.1 Site Selection and Description

Water bodies that are affected by water hyacinth contain common pollutants. These include industrial and domestic wastes, municipal effluents and agrochemicals like fertilizer, all of which fosters the growth of water hyacinth. The inlets of these effluents are located at specific points within the respective water bodies. The effluent concentrations vary from point to point within the affected water bodies. Water hyacinth has affected several water bodies around the world. In Kenya, Lake Victoria and Nairobi dam are the environmentally friendly water bodies that have been adversely affected as a result of eutrophication, leading to ecological imbalance. Nairobi dam was chosen for this study since it has a smaller surface area of 356.2 km^2 compared to 68,800 km^2 for Lake Victroria. This small size enabled samples to be taken at all the four sides of the dam that were thought to have varying effluent concentration. The dam also had an advantage over Lake Victoria in that its distance to the laboratory where triaxial testing was to be done was shorter (less than 20 km) compared to approximately 350 km to lake Victoria. As a result of the short distance, samples were transported for dewatering on the same day, hence the *in-situ* sample conditions were maintained.

Nairobi dam is located at approximately 7 km from Nairobi (1°16'S latitude and 36°48'E longitude), the capital city of Kenya at an altitude range of between 1680 and 1700 m above sea level. Motoine River is the main inlet into the dam. Motoine leaves the dam as Ngong River and cascades through South C area and Industrial area. The average depth of the dam is 2.76 m. The dam volume is 98, 422 m^3. The rains in the region come around April-May and November-December with accumulative over dam precipitation of about 875 mm per annum. The total contribution of rainfall to the dam is 311,656 m^3 per year. Average temperature within the area is 21^{o}C. The total loss of water as a result of evapotranspiration from water hyacinth is about 711,289 m^3 per annum (Ndede, 2002)

2.2 Field Sampling

Samples were collected from four different locations within Nairobi dam namely: S1, next to Nairobi Yacht club; S2, on the same side as Kibera slums; S3, on the same side as Kibera High rise estate and S4, on the same side as Mbagathi road. This was to take care of any possible biophysical and chemical variability that might have influence on the experimental investigation.

Whole live water hyacinth plants were uprooted from these locations and packed in labelled polythene bags, which were transported to the laboratories for dewatering. Water was poured in the polythene bags above the root levels of the plants and plants allowed to stand in tabs to prevent drying as they await sample preparation. This was to keep them alive, fresh and to avoid the risk of wilting by enabling a fairly constant water content that duplicates the field conditions as reported by Book (1969).

2.3 Laboratory Sample Preparation

Water hyacinth petioles were separated from the leaves and roots by cutting off the leaves and the roots respectively using a sharp knife. The petioles were then chopped into cylinders of 30 mm length. The chopped petioles were then split into half cylinders so as to expose the large air spaces that are found in the petioles. Sample lengths of 30 to 50 mm have been used by Spatz *et al*. (1999) while Wagner and Büscher (2005) used higher length (45 and 90 mm) of cut when working on wilted grass.

2.4 Experimental Layout

The identified parameters were investigated by conducting consolidated drained triaxial compression tests to dewater (predetermined weight of water hyacinth) petiole samples.

2.4.1 Dewatering

The digital 'tritest' model 50 shown in Figure 2 was used in this experimental investigation. The system has four ports and 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 cell is capable of withstanding pressure of up to 1.7 MPa.

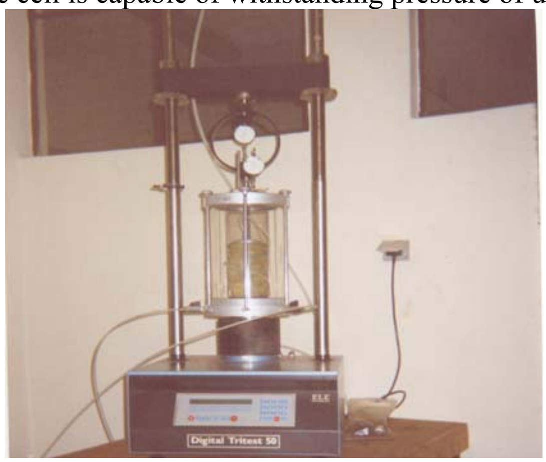

Figure 2. Triaxial test equipment assembly during experiment

Figure 3 shows the three compressive stresses at right angles to each other during triaxial compression. The specimens were enclosed in rubber membranes and ends placed between porous caps with drainage ducts to allow movement of water from the specimens. Axial loads were applied to the specimen through a loading rod which was in contact with the top of the specimen, throughout the experiment.

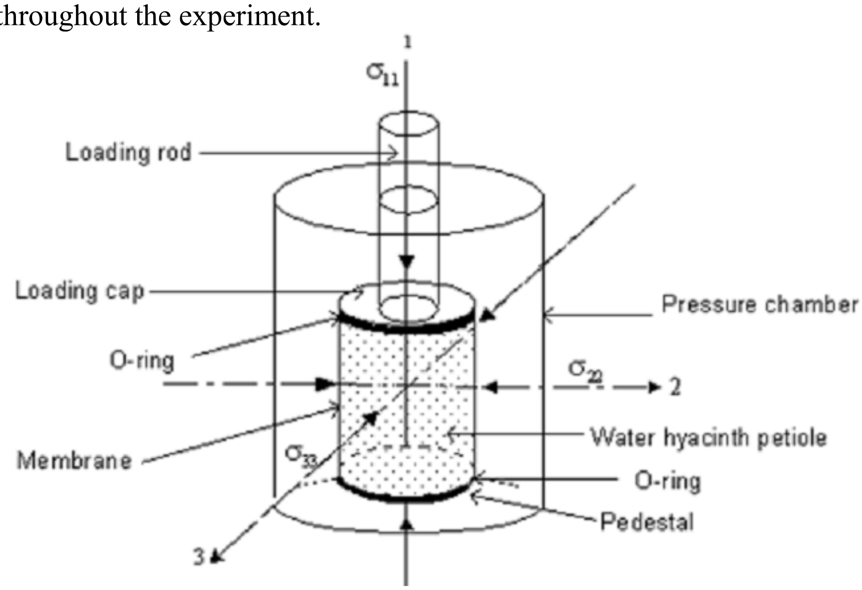

Figure 3. Basic triaxial cell with specimen under compression

A 4.5 kN clamped boss load ring with a design sensitivity of 3.0 N/mm (calibration constant) was used in loading the specimen. Confining stress (σ_{33}) were set at 300, 400, 500 and 600 kPa. Cifuentes and Bagnall (1976) established that expelled fluid increased rapidly with increasing confining stress up to 600 kPa, but higher stress did not remove much more fluid. The specimens were compressed in the axial direction at a dynamic rate of 1 mm/min. This strain rate is within the range used by numerous researchers. For instance Wiedemann and Neinhuis, (1998) used a strain rate of 2 mm/min while Oey *et al.*, (2006) used 0.2 mm/min. The expelled fluid that came from the bottom drainage of the triaxial machine was allowed to pass through a funnel that was fitted at the bottom drainage and then collected in a measuring cylinder as shown in Figure 4. Details of the triaxial experimentation have been given by Gitau *et. al.,* (2006) and Gitau and Gumbe (2007).

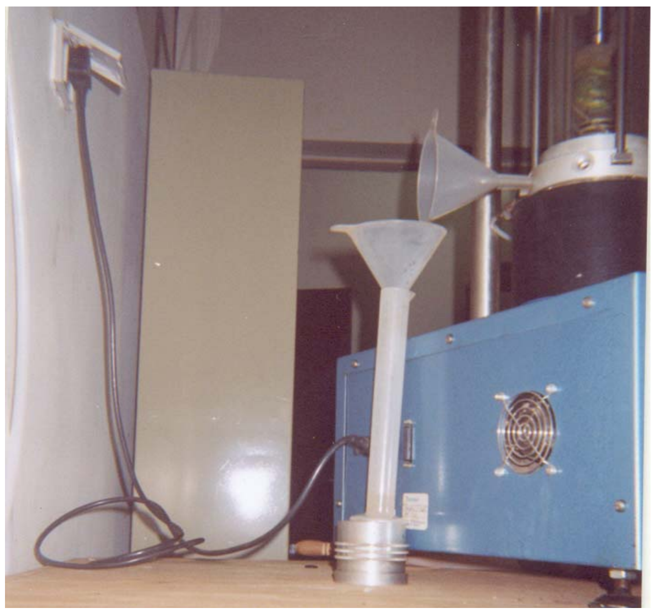

Figure 4. Collection of expelled fluid from triaxial machine

The dewatered samples were weighed, packed in labelled plastic bags and stored in a refrigerator set at the lowest design temperature of 12^{o}C to keep them fresh and prevent moisture loss or gain.

2.5 Development of Predictive Equations

Tensors are abstract objects whose properties are independent of the reference frames used to describe them. Tensors are classified as Zeroth, First, Second, Third or Fourth order depending on the number of indices of the tensor. Thus, σ_i and σ_{ij} are first and second order tensors respectively. Isotropic tensor is tensor having the same components in all orthogonal coordinate system (Oranga, 2005 and Chung, 1996). In Figure 2; $\sigma_{11,}\ \sigma_{22}$ and σ_{33} are the principle stresses in which σ_{11} act axially and σ_{22} and σ_{33} are orthogonal to σ_{11}. In triaxial testing conditions $\sigma_{22} = \sigma_{33}$, therefore the deviatoric stress(q) that causes deformation is given by :

$$q = \sigma_{11} - \sigma_{33} \qquad [1]$$

From the axial displacements, axial strain (ε) and hence strain rates $(\dot{\varepsilon})$ were computed. Plots of deviatoric stress against strain rates were made to observe the shape of the deviatoric stress-strain rate curves. Since one of the major interests of the experiment was to dewater the samples, deviatoric stress was plotted against the rate of expelled fluid during dewatering. Exponential series model of the form;

$$q = A\exp(B\dot{w}) \qquad [2]$$

and a power series model of the form;

$$q = a\dot{\varepsilon}^{-b} \qquad [3]$$

were used in the triaxial experiments.

Where:

q = Deviatoric stress
$\dot{w}$ = Rate of expelled fluid
A, B, a, b are experimental constants

One-way ANOVA to determine whether there is a significant difference of the mean initial moisture content of the samples at the four sampling locations showed strong indication that the location of sampling within the dam did not affect the initial moisture contents for 16 determinations at a significance level of 0.05 with a P-Value of 0.94.

These findings described dewatering characteristics of water hyacinth petiole accurately for the identified pertinent parameters.

3. RESULTS AND DISCUSSION

3.1 Dewatering

Continuously increasing deviatoric stress expelled fluid from water hyacinth petiole samples. Table 2 shows the amounts of expelled fluid resulting from the effect of increasing deviatoric stress at various confining stresses. Statistical analysis showed that there was a 95% confidence level that the mean volume of expelled fluid during dewatering was 20.66 ml (SD = 3.5, n = 16) as at the point of sample failure. One way ANOVA showed an indication that the confining stresses did not affect the amount of expelled fluid from the samples at a significance level of 0.05 with a P-value of 0.83. The expulsion of fluid from water hyacinth petiole could be attributed to the effect of deviatoric stress of water hyacinth petiole. Dewatering could not expel all the fluid from the samples possible due to its high moisture content retention.

3.1.1 Deviatoric Stress against Expelled Fluid

Figure 5 is a graphical representation of the relationship between deviatoric stress and expelled fluid for sample dewatered at different confining stresses.

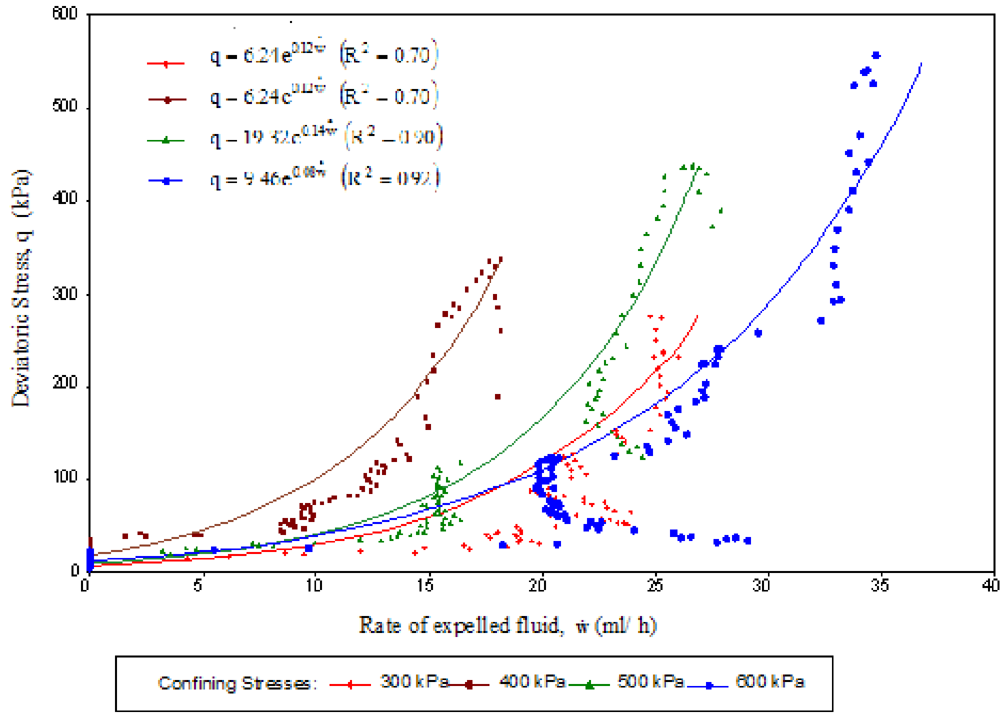

Figure 5. Deviatoric stress against the rate of expelled fluid.

The rate of expelled fluid for the sample increased irregularly with increase in deviatoric stress. At the initial stages of dewatering, there was a high increase in the rate of expelled fluid at a lower deviatoric stress of below 50 kPa. This increase proceeded up to a rate of expelled fluid of around 10 ml/hr beyond which the increase in the rate of expelled fluid slowed down but remained proportional to the increase in deviatoric stress. These curves have a general upward exponential trend. It was noted from the graphs that at the initial stages deviatoric stress (q) increased at zero strain rates and subsequently fluids started coming out of the sample matrix. The mean deviatoric stresses required for expelled fluid to be realised were 20.85, 34.90, 29.75 and 28.19 kPa at confining stresses of 300, 400, 500 and 600 kpa. The respective standard deviations were 4.33, 5.09, 7.90 and 2.82 kPa. The graphs also depicted that small amount of deviatoric stress (q) produced larger volumes of water at the initial stages. This could be attributed to saturation of samples with high moisture content. The exponential predictive equation used to model the deviatoric stress-expelled fluid relationships adequately modelled the water hyacinth petiole behaviour, showing high values of coefficient of determination (R^2 greater than 0.70). These results are in agreement with those obtained by numerous researchers. Sinha *et al*. (2000) obtained similar results when they conducted compressive tests on chopped alfalfa, using piston cylinder assembly, showing that compressive stress affects the amount of juice expelled from alfalfa. The results of their investigations conformed to those obtained by Holdren *et al.* (1972).

3.1.2 Deviatoric Stress-Strain Rate

In order to perceive the effect of the deviatoric stress on strain rate, the two parameters were plotted as shown in Figures 6.

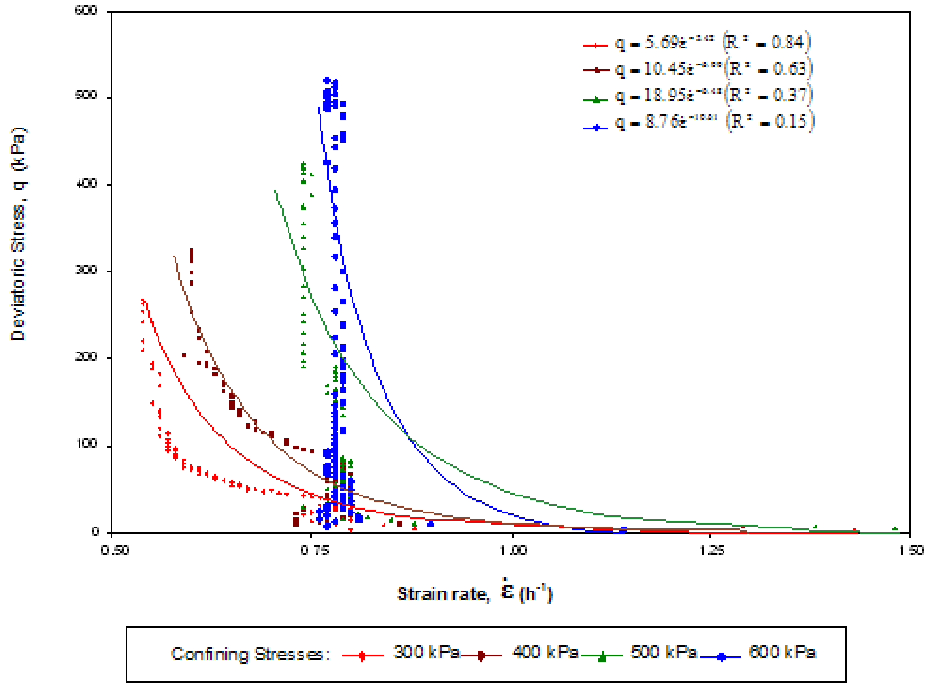

Figure 6. Deviatoric stress against strain rate for sample at confining stresses of 300, 400, 500 and 600 kPa.

The graph depict that when deviatoric stress was zero then there was no strain applied to the samples. The highest strain rate at which deviatoric stress begun to be realised in the samples was around 1.5 h^{-1}. This value was then observed to decrease to a strain rate below 0.75 h^{-1}, but no passing the 0.5 h^{-1} mark, where the strain rate remained constant as deviatoric stress increased. This could be attributed to the time required to break the structure of the sample material such as cell wall. In plant tissue, cell wall is the dominant load bearing feature that determines structure (Javis, 1984). A substantial non-linear curve is observed just before accumulation of deviatoric stress and a constant strain rate begun. At this stage, compression of water hyacinth petiole was dominated by fibre compression. Therefore the properties of the fibre governed the stress behaviour. This was caused by the end of fibre movement through repositioning and filling of the air spaces within the sample and the strain rate became constant. Haman *et al.* (1999) reported similar behaviour while working on potato tuber. Such behaviour can be attributed to the difference between the compressive strength of fiber and other cell tissues within water hyacinth petiole. The strain rate then remained constant with an increase in deviatoric stress and eventually the curve snaps abruptly. The graph also shows a general decline in trends of coefficient of determination (R^2) with increasing confining stresses. This observation is ascertained by one-way ANOVA that showed a weak indication (P-Value of 0.004) that confining stresses did not affect coefficient of determination. This could be attributed to resistance that builds in the sample during consolidation at higher confining stresses. Figure 5 shows the trend of the deviatoric stress against modulus of elasticity. The graphs gave decreasing modulus of elasticity at the initial stages of the experiment followed by increasing modulus of elasticity when strain got larger, showing strain softening at the initial stages of the experiment followed by strain hardening respectively. There was also a transition point between the strain softening and strain hardening phases. This trend revealed considerable changes in the mechanical properties of water hyacinth petiole. Further analysis to ascertain these mechanical changes at mean values of modulus of elasticity at 20% strain and 80% stress gave mean modulus of elasticity at 20% strain as 269.42 kPa (SD = 47, n = 16). While the mean modulus of elasticity at 80% stress was 599.48 kPa (SD = 160 n = 16). Oey *et al*. (2006) obtain similar results with modulus of elasticity at 20% strain and 80% stress.

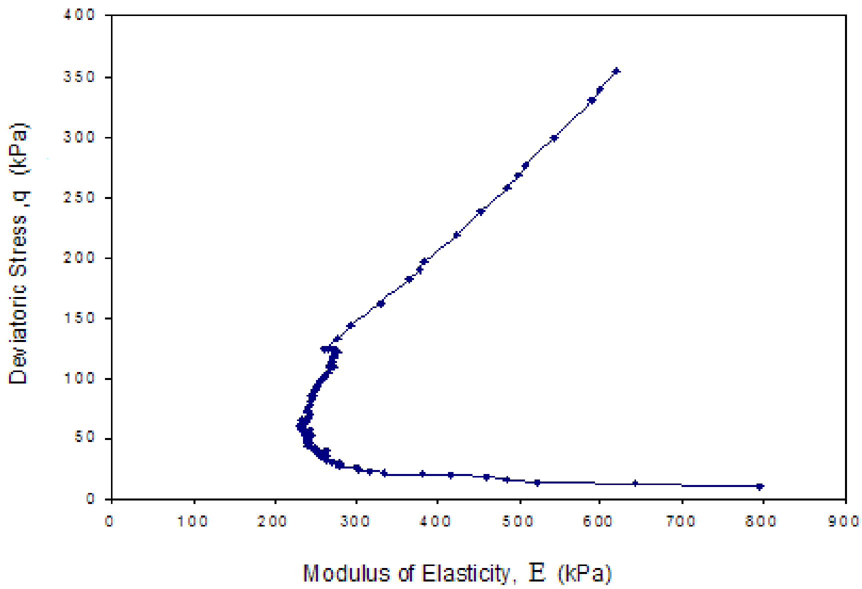

Figure 7. Decreasing and increasing modulus of elasticity for dewatered sample

Table 3 shows the individual values of modulus of elasticity at 20% strain, and at 80% stress. At 20% strain the samples still undergoes sizeable deformation that is why there is a significant difference in the mean values of elastic modulus between 20% strain and 80% stress. The fact that the sample fibres and tissues are not strained to the same extent and that the material apparently changed its mechanical properties as evidenced by decreasing modulus followed by an increasing modulus via a transition phase ascertains that water hyacinth petiole exhibits a plastic deformation at the initial stages of loading when treated as a continuum.

Table 2. Modulus of elasticity, E (kPa) at 20% and 80%strains respectively.

Sample	**Confining Stress, σ_{33} (kPa)**							
	300		**400**		**500**		**600**	
S1	181.4	519.0	238.7	477.8	305.5	598.0	291.2	431.2

Sample	Confining Stress, σ_{33} (kPa)							
	300		400		500		600	
S2	310.3	401.0	276.9	532.8	200.5	695.4	324.6	482.4
S3	262.6	641.0	305.5	776.5	267.3	440.8	238.7	923.8
S4	267.3	441.2	253.0	635.9	224.4	752.2	362.8	842.6

However the subsequent increasing modulus of the material during further loading depicted viscoelastic behaviour. Dai and Steiner (1993) found that wood-fiber mats behave in a similar manner, governed by lower compressive stress in the initial stages of compression. These results are in agreement with that of Lang and Wolcott (1996) who observed that a substantial amount of plastic deformation occurred with increase in stress in a loosely formed wood strand-mat. ANOVA analysis for water hyacinth petiole modulus of elasticity at 20% stress showed a weak indication (P-value of 0.38) that confining stresses did not affect the modulus of elasticity, as opposed to a fairly strong indication (P-value of 0.54) given by the analysis at 80% stress, at a significance level of 0.05.

4. CONCLUSIONS

Deviatoric stress caused fluid to be expelled from water hyacinth petiole medium. It was easier to expel intercellular fluid at the initial stages of compression since they are saturated compared to intracellular fluid which required further progressive mobilisation of deviatoric stress to be expelled. General strain rate was observed to decrease in three stages of fast, slow and constant strain rates. These were linked to: breakage of water hyacinth sample structure to expose the voids and large airspaces; repositioning of sample fibre to fill the exposed voids and large air spaces; governing of deviatoric stress-strain rate behaviour by fibre compression properties respectively. Investigation results showed strain softening at the initial stages of the experiment followed by strain hardening respectively. The observed mechanical changes shows that water hyacinth petiole fibres and tissues are not strained to the same extent. The abrupt disintegration of the curve observed at failure indicated that water hyacinth petiole has brittle fiber.

The dewatering models in this study should be verified using other dewatering techniques such as centrifugal techniques besides pressure application.

5. ACKNOWLEDGEMENTS

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NOMENCLATURE

q	Deviatoric stress
$\dot{w}$	Rate of expelled fluid
$\dot{\varepsilon}$	Strain rate
h^{-1}	Per hour
σ	Compressive strength
R^2	Coefficient of determination