Some Rheological and Frictional Properties of Soils and Agricultural Grains

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Abstract

Rheology, the study of time-dependent flow and deformation of a material, expresses its mechanical behaviour in terms of force, deformation and time or stress, strain and time. The granular nature of soils and agricultural grains presents an interesting factor in soil and water studies in relation to agricultural production - the flow through soil and the grains being governed by flow through porous media. Soil rheological properties are important in soil compaction, tillage, soil- machine studies and other agricultural operations. Rice (oryza sativa), maize (zea mays), sorghum (sorghum spp.), beans (vigna sinensis) and gari (obtained from cassava, manihot esculanta) are food crops. Rice is a staple food common in most African diets. Rheological tests were conducted on soil samples and on rice, maize, sorghum, beans and gari, using an Instron Universal Testing Machine. Shear box tests were also conducted on the materials to determine their shearing resistance. For the agricultural grains, the Young's Modulus (Modulus of Elasticity) ranged from 22.37 N/ mm^2 (for gari) to 85.79 N/ mm^2 (for rice). The angle of internal friction for the soils ranged between $30^0\ 57^/$ and $34^0\ 17^/$ while, for the agricultural grains, ranged from 23^0 (sorghum) to 39^0 (gari). This work provides experimental data for use in rheological and geotechnical models and in the design of machines and processes/ operations for handling these materials.

***Keywords**: Rheology, Frictional properties, Soils, Agricultural grains.*

1. Introduction

Rheology could be defined as the study of time - dependent flow and deformation of a material. Rheology is thus the mechanical behaviour of a material expressed in terms of force, deformation and time or stress, strain and time. Agricultural materials are biological in nature and are frequently subjected to different mechanical forces during production, processing, harvesting, handling, transportation and storage. Thus, a knowledge of the mechanical and rheological properties of biomaterials will facilitate the design of machines and processes for handling them.

Mohsenin (1984, 1986), Sitkei (1986) and Tsytovich (1986) defined some terms relevant to the study of rheological properties. The bioyield point is the point on the stress - deformation curve at which the stress decreases or remains constant with increasing deformation. This point reflects the sensitivity of the biomaterial to damage. The rupture point indicates failure over a significant volume of the material. Beyond the rupture point, the stress decreases rapidly with increasing deformation. The amount of energy or work required to bring about rupture in the material indicates its toughness. It is the area under the force - deformation curve before the rupture point. The Young's Modulus is the gradient of the initial straight line portion of the stress - strain curve. While several investigations have been conducted on the engineering properties of agricultural products (Zoerb and Hall, 1980; Igbeka, 1984; Mohsenin, 1986; Guzel et al. 2005), relatively few works have been carried out on the rheological properties of soils and some tropical grains. Igbeka (1984) investigated the mechanical and rheological properties of two tropical root crops, yam and cassava. The properties investigated were stress - relaxation, modulus of deformability, shear and compressive energy at failure, degree of elasticity and hysteresis loss. Gupta and Pandya (1966) described the soil as a deformable body whose behaviour falls between a linear elastic solid and an ideal viscous liquid. Soil was described as a non – linear viscoelastic solid while its behaviour under static loading could be expressed by a stress – strain – time relationship.

The granular nature of soils and agricultural grains presents an interesting factor in soil and water studies in relation to agricultural production – the flow through soil and the grains being governed by flow through porous media. Soil provides a medium for plant growth. It is also an important material in the construction of buildings and other structures. Soil rheological properties are important in soil compaction, tillage, soil – machine studies and other agricultural operations. Frictional properties, dependent on shape and surface roughness of individual grains, affect the extent of packing of a material and therefore influence seepage and aeration. Marchant (1980) suggested the formulation of stress- strain law that is applicable to any type of bulk granular material. It was pointed out that both soils and grains are granular materials and thus their stress- strain properties should have similar forms. The model parameters were used for a sample of wheat to predict the strains occurring for different loading conditions. Rice (*oryza sativa*), maize (*zea mays*), sorghum (*sorghum spp.*), beans (*vigna sinensis*) and gari (*obtained from cassava, manihot esculanta*) are food crops. Rice is a staple food common in most African diets. Maize, beans and gari are also consumed by humans and put to other uses, including being major components in other foods/ diets. The objectives of this work were to provide experimental data for use in rheological and geotechnical models and in the design of machines and processes/ operations for handling these materials.

2. Materials and Methods

Samples of sandy soil and clayey soil, taken at two locations in Ilorin, Nigeria, were used in the experiments. Ilorin (Longitude $4^0\ 35^/$ N), the capital of Kwara State of Nigeria, experiences two seasons: the wet season usually begins in March and ends in October while the dry season falls between November and February. The mean annual rainfall is about 1222 mm. Mean monthly temperature varies from about 25 ^{0}C to about 29 ^{0}C. The relative humidity varies from about 70 % in the dry months to about 80 % in the wet months (Oyegun, 1983; Akintola, 1986). The soils have been classified as belonging to the order of alfisols – Tropeptic Haplustalf (Soil Survey Staff, 1975). Rice (*oryza sativa*), maize (*zea mays*), sorghum (*sorghum spp.*), beans (*vigna sinensis*) and gari were also used in the experiments which were conducted with an Instron Universal Testing Machine, UTM (Testometric Model M500 – 50 kN) using a test speed of 2.5 mm/ min.

For the rheological properties, the experiments were conducted at the following moisture contents (% dry basis), determined using gravimetric method: sandy soil (9.8 %), clayey soil (11.3 %), rice (4.3 %), maize (3.7 %), sorghum (8.7 %), beans (9.9 %) and gari (10.3 %). The samples were prepared for the experimental tests using a cylindrical core with a height of 70 mm and diameter 44 mm, giving a height / diameter ratio of 1.59. Force – deformation curves were generated from the Universal Testing Machine (UTM). Shear box tests were also conducted at normal loads of 5 kg, 10 kg, 15kg and 20 kg, to determine the shearing resistance of the materials.

3. Results and Discussion

The experimental data on rheological properties are presented in Table 1 while the soil, frictional and grain properties are presented in Table 2. The energy at peak was 35.53 N.m for the sandy soil and 50.54 N.m for the clayey soil, and ranged from 98.97 N.m (for sorghum) to 136.37 N.m (for rice) for the agricultural grains. The strain at peak was 53.16 % for the sandy soil and 30.21% for the clayey soil, and ranged from 18.79% (for rice) to 40.27% (for gari) for the agricultural grains. Modulus of Elasticity (Young's Modulus) values of 92.09 N/ mm^2 and 42.00 N/ mm^2 were obtained for sandy and clayey soils, respectively; while, for the agricultural grains, ranged from 22.37 N/ mm^2 (for gari) to 85.79 N/ mm^2 (for rice).

The bulk and particulate properties of the materials are important in processes involving them. The bulk density values for the soils ranged between 1.57 g/ cm^3 and 1.70 g/ cm^3, and, for the agricultural grains, between 0.76 g/ cm^3 (gari) and 1.14 g/ cm^3 (beans). Particle density consideration is essential in separation processes and in pneumatic and hydraulic conveyance of particles. The particle density ranged from 2.40 g/ cm^3 to 2.60 g/ cm^3 for the soils, and from 1.25 g/ cm^3 (beans) to 1.88 g/ cm^3 (sorghum) for the agricultural grains. Porosity is important in seepage and aeration studies. For the soils, porosity ranged from 0.30 to 0.37.

The angle of internal friction (shearing resistance angle) ranged from $30^0\ 57^/$ to $34^0\ 17^/$, for the soils; while it ranged from 23^0 (sorghum) to 39^0 (gari) for the grains. The cohesion (c) values are also shown in Table 2. Thus, for a known compressive stress, the shear stress could be predicted using Coulomb's equation: (Tsytovich, 1986):

$$\tau = c + \sigma \tan \Phi \qquad (1)$$

where:

τ = shear stress

σ = compressive stress

C = cohesion

Φ = angle of internal friction

These results are applicable to soil compaction and tillage studies and other agricultural operations including those involving air – and heat – flow. The moisture content and changes in pore space from applied stresses are important consideration in these studies.

4. Conclusions

Rheological tests were conducted on soil samples and agricultural grains (rice, maize, sorghum, beans and gari) using an Instron Universal Testing Machine (UTM). Shear box tests were also conducted on the materials. The rheological and frictional properties were affected by moisture content and material physical properties. The results are useful in rheological and geotechnical models, soil tillage and compaction studies and in the design of machines and structures for handling and storing the materials.

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Table 1. Experimental data on rheological properties

Sample	Load at Peak (N)	Stress at Peak (N/mm^2)	Strain at Peak (%)	Load at Break (N)	Stress at Break (N/mm^2)	Strain at Break (%)	Load at Yield (N)	Stress at Yield (N/mm^2)	Strain at Yield (%)	Young's Modulus (N/mm^2)	Energy at Peak (N.m)	Energy at Yield (N.m)
Sandy soil	15086	9.92	53.16	15086	9.92	53.16	-	-	-	92.09	35.53	-
Clayey soil	15628	10.28	30.21	15628	10.28	30.21	-	-	-	42.00	50.54	-
Rice	25032	16.46	18.79	25032	16.46	18.79	5482.0	3.61	6.24	85.79	136.37	9.11
Maize	15085	9.92	28.95	15085	9.92	28.95	3460.0	2.28	12.51	31.06	104.26	10.10
Sorghum	15034	9.89	39.82	15034	9.89	39.82	5147.0	3.39	28.69	26.83	98.97	26.66
Beans	15015	9.87	29.49	15012	9.87	29.50	3197.0	2.10	10.97	24.62	113.79	11.78
Gari	15031	9.89	40.27	15031	9.89	40.27	5015.1	3.30	27.75	22.37	109.81	28.77

Table 2. Soil and grain properties

Sample *	Moisture content (% dry basis)	Particulate density (g/ cm^3)	Bulk density (g/ cm^3)	Porosity	Friction angle; Φ	Cohesion, c (kN/ m^2)
Soil A1	17.14	2.40	1.68	0.30	30^0 57	20
Soil A2	10.00	2.45	1.59	0.35	$34^0\,17^/$	15
Soil B1	3.57	2.50	1.57	0.37	$33^0\,41^/$	16
Soil B2	5.00	2.60	1.70	0.35	$30^0\,57^/$	12
Rice	7.14	1.55	1.04	0.33	29^0	105
Maize	5.13	1.36	1.12	0.18	23^0 44	70
Sorghum	8.51	1.88	0.94	0.50	23^0	18
Beans	5.41	1.25	1.14	0.09	$29^0\,31^/$	12
Gari	5.41	1.67	0.76	0.54	39^0	35

*Soil A1 = Clayey soil sample at 0 – 70 mm depth

Soil A2 = Clayey soil sample at 70 – 140 mm depth

Soil B1 = Sandy soil sample at 0 – 70 mm depth

Soil B2 = Sandy soil sample 70 – 140 mm depth