Design, construction and evaluation of shear vane device for biomass yield stress determination

Heman Amiri, Akbar Arabhosseini*, Mohammad Hossein Kianmehr

(*Department of Agrotechnology*, *College of Abouraihan*, *University of Tehran*, *Tehran*, *Iran*)

Abstract: Agglomerate followed by pelleting is one of the efficient methods to decrease transport costs and increase economic efficiency of biomass material. Understanding the rheological properties of biomass is necessary for optimization of pelleting process as well as the design of devices with enough energy and pressure to determine the effect of different variables on the density and durability of pellets. The rheological properties of extruded material are depended upon properties and moisture content of the raw materials, used for extrusion. Therefore, in this study a shear vane was developed to determine the rheological properties of biomass materials. The output rotation of the electromotor was measured by a rotary encoder. The forces inserted by the material to the vane blades were measured by a bending loadcell. The experiments were done at moisture content levels of 35%, 40% and 45% (w.b.), and rotational speed of the shear vane container at three levels of 0.1, 0.2 and 0.3 r min^{-1}. The results showed that the higher peak of torque was achieved at 35% moisture content and rotational speed of 0.1 r min^{-1}, while the lowest peak of torque was obtained at 35% moisture content and rotational speed of 0.2 r min^{-1}. The maximum torque (2.25 N.m), maximum shear stress (4.70 kPa) and maximum yield stress (5.05 kPa) were obtained at 35% moisture content and rotational speed of 0.1 r min^{-1} while the minimum torque (1.12 N.m), minimum shear stress (2.32 kPa) and minimum yield stress (2.50 kPa) were obtained at 35% moisture content and rotational speed of 0.2 r min^{-1}.

Keywords: cow manure, development, performance evaluation, shear stress, shear vane device, torque, yield stress

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1 Introduction

The biomass materials such as animal manures and compost materials have low density. The transportation and storage costs of these materials are high because of high volume. Handling and spreading of them in the fields and gardens are also costly. Pelleting is one of the methods to provide an effective platform for optimal use, low transport costs and high economic efficiency in the use of these materials. Information about physical and rheological properties of the materials as well as some of the design factors is necessary for the design of press equipment in order to produce pellets in optimal shapes and conditions. Knowledge about physical and rheological properties of the materials is needed for the design of pelleting device. The press equipment conditions and the properties are necessary to calculate the required power for pelleting (Sitkey, 1986).

Rotational viscometer is useful for the characterization of non-Newtonian fluid behavior. Viscometers are available in two types with the controlled shear rate instruments and controlled stress instruments. Various devices have been designed for measurement of rheological properties, especially viscosity measurements of liquid, semi liquid and pasty materials that may have different working principles. The methods based on fundamental viscometers are divided into two major categories of tube and spin (Ghanbarzadeh, 2009).

Using rotational viscometers is one of the techniques to measure the visco-elastic properties of materials. These viscometers are called vane type or shear vane.

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*** Corresponding author: Akbar Arabhosseini**, Dept. of Agrotechnology, College of Abouraihan, University of Tehran, Pakdasht, 3391653755, Tehran, Iran. Tel: +98 (21) 360 40 614; Fax: +98 (21) 360 40 730. Email: ahosseini@ut.ac.ir.

The shear vane measurement technique involves slow rotation of a vane immersed in the sample trial and measuring the resulting torque as a function of time. The torque can be converted to shear stress by making several assumptions (Poloski et al., 2004).

The shear vane has been employed for measuring strength properties of soils in situ (Gill and Vanden Berg, 1967) because of the ease and convenience of such measurements.

Landry (2002) used shear vane to measure the rheological properties of animal manures. The rheological properties of sheep, poultry, pigs and cows manure were examined at different levels of concentration of solids in two phases of solid and semi-solid.

Karmakar (2005) used a shear vane to evaluate the dynamic soil parameters. He had built a device that could be used to study the viscosity and yield stress of the soil. In this device the blades are moved by gears and chains are driven by an electromotor. The blades were immersed into the soil inside the container. During the rotation of the blades inside the soil, the exerted force by soil was registered and sent to data logger.

Some other researchers are presented the derivation of mathematical relationship between torque and speed during shearing in concrete rheometer with vane geometry. An expression has been derived for total shear stress to present the shear stress versus torque and shear strain rate versus rotational frequency relationships. It has been established for the vane geometry of a concrete rheometer (Laskar and Bhattacharjee, 2011).

A Lagrangian formulation of the Navier–Stokes equations were applied, based on the smoothed particle hydrodynamics (SPH) approach, to determine how well rheological parameters such as plastic viscosity can be determined from vane rheometer measurements. The validity was tested by comparing the calculated stress and flow fields between the two rheometers. The validation was based on the assumption that the vane could be approximated as a cylinder for measuring the rheological properties of Bingham fluids at different shear rates (Zhu et al., 2010).

The objectives of this study were to develop a shear vane device for the determination of biomass visco-plastic parameters and performance evaluation of the shear vane.

2 Materials and methods

2.1 Development of shear vane

A motorized shear vane was developed at the Department of Agrotechnology, College of Abouraihan, University of Tehran in order to evaluate the rheological parameters of biomass. The apparatus is capable of measuring biomass yield stress. There are two main differences between the existing equipment and the designed apparatus. In the existing equipment the test container is fixed and the blades rotate inside the container while in the designed apparatus the situation is vice versa. The other difference is that in the existing equipment the torque is determined by a torque meter that is fixed on the blade spindle while in this apparatus a loadcell was used for measuring the force. Then the force is used for calculation of the required torque.

The shear vane apparatus consists of shearing vane and vane spindle, test container, vertical displacement vane mechanism, motion transmission mechanism and driveline, data acquisition system and the main-frame.

2.2 Vane and test container

The shearing vane and the spindle were designed using commercial computer aided design software Solidworks2007. The diameter of the vane spindle and its length were found to be 12.5 mm and 114.3 mm respectively. The vane-holding end of the spindle was protruded to hold the vanes in the slots. The vane spindle was tested for the torsional strength.

The shearing vane was made of a standard size specified by the ASTM standards (Figure 1). The following conditions were considered for manufacturing of blades: $Z_1/D_v \geq 1.0$ or $Z_1 = 0.0$; $Z_2/D_v \geq 0.5$ and $1.5 \leq H/D_v \leq 4.0$. In this model the portion of $D/D_v \geq 2.0$ was selected because the blade was completely immersed into the material (Landry et al., 2002; Steffe, 1992).

A sheet with a thickness of 2 mm was used for making the blades with the above-mentioned dimensions in order to keep standard aspects. A round steel bar with diameter of 50 mm was used for making the shaft

(Figure 2).

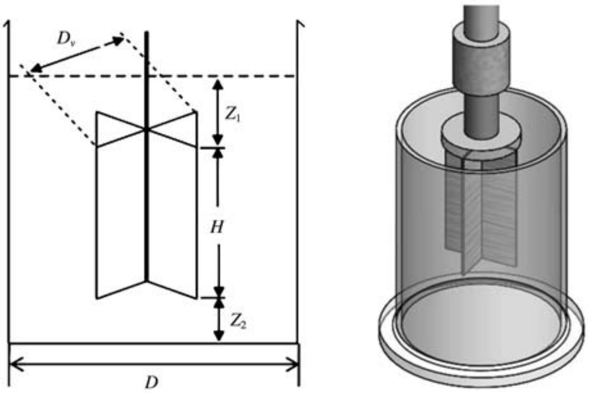


Figure 1 Dimensions of the shear vane blades designed by using SolidWork2007 software

Figure 2 Standard blade made for the shear vane

A coupling system was built for connection of the blades and the shaft of the torque arm. The shaft was fixed by using four screws on the sides.

A standard steel pipe with diameter of 165 mm was used for the container. The bottom of the container was closed using a round steel sheet (Figure 3).

Figure 3 Shear vane container and its connection to the shaft of electromotor

2.3 Vertical displacement of vane mechanism

A mechanism consisting of a bolt and nut and two rod holders was used to provide the vertical motion of the blade in order to adjust its height position. The vertical displacement of the blades would occur by turning the handle, attached to the bolt, which causes the movement of the nut on the bolt in the direction of its conductor bars.

An angled iron was fixed on the bolt in order to assemble the loadcell and the sits of the torque arms. The torque arms are connected to the vane. The other parts move by moving the bolt (Figure 4).

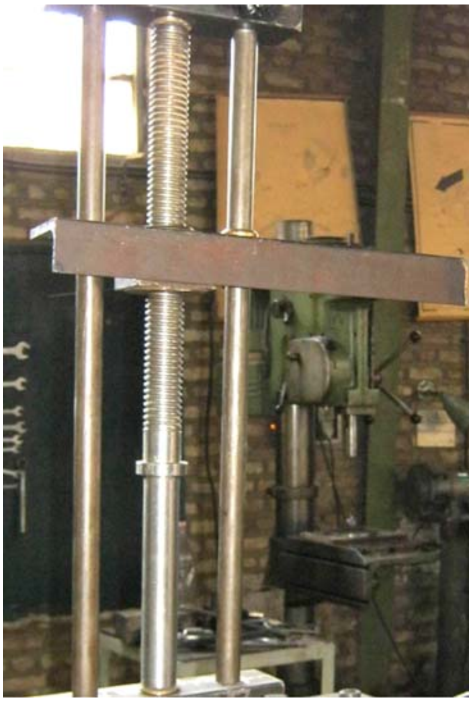


Figure 4 Vertical displacement mechanism

An inverter (SVO 15i C5-1F, Korea) was used to control the speed of the motor (0.5 kW, 1,370 r $\min^{-1}$ at 50 Hz) for rotating the container at different speeds. Two speed reducers were used in line for providing the rotational speed of the motor which is close to the required speed. The reducers consisted of worm gearboxes with speed ratio of 12:1 for reducer 1 and speed ratio of 16:1 for reducer 2 (Figure 5).

A rotary encoder (E50S8-60-3-T-24, AUTONICS, Korea) was used, to measure the output rotation of the electromotor shaft. The encoder was installed on the output shaft by replacement of the fan (Figure 6). In fact, the output was reduced by invertors and the rotation was measured by using the rotary encoder and then displayed digitally. The registered rotation was multiplied by speed ratios of the reducer 1 (12:1) and reducer 2 (16:1) to have the actual rotation.

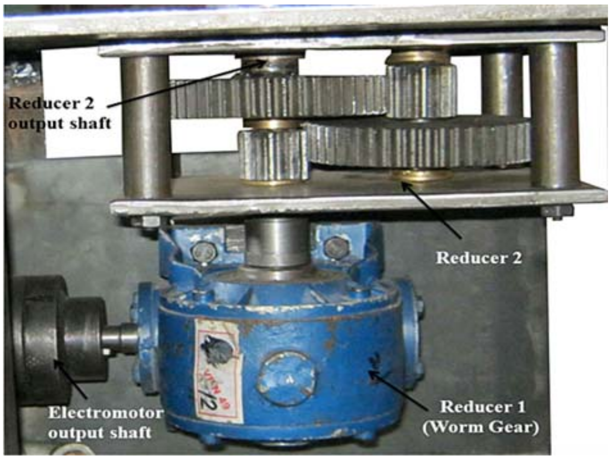


Figure 5 Reducer mechanisms of the electromotor

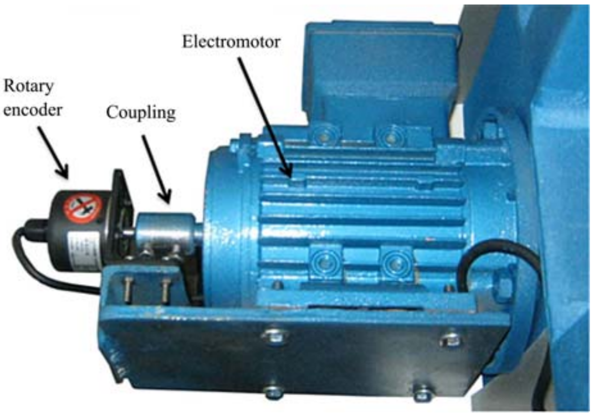


Figure 6 Location of encoder on the electromotor

2.4 Data acquisition system

A loadcell (L6D-C3-10Kg-0.4B, ZEMIC) was used to measure the forces. A shaft was coupled to the vane and an arm was added at the end of the shaft. The loadcell was installed on the arm and the other side of the loadcell was fixed on the frame. The material between the vane and the container impacts forces on the vane. The force will be transferred to the loadcell via the arm to measure the torque (Figure 7).

The encoder transfers the rotational speed of the electromotor to the electronic board. The board is able to analyze the input data and monitor the output results on the screen. The board also transfers the recorded data to Excel sheets. The board consists of microcontroller (AVR ATMEGA 128), USB port, digital converter (AD7715) and LCD 128 × 64 (Figure 8).

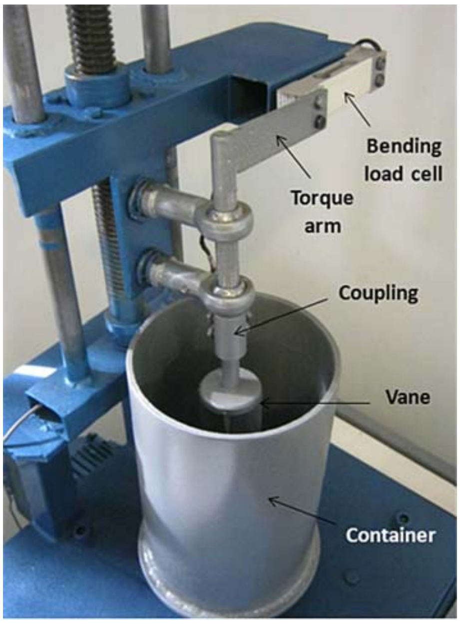


Figure 7 The bending loadcell connected to the vane shaft

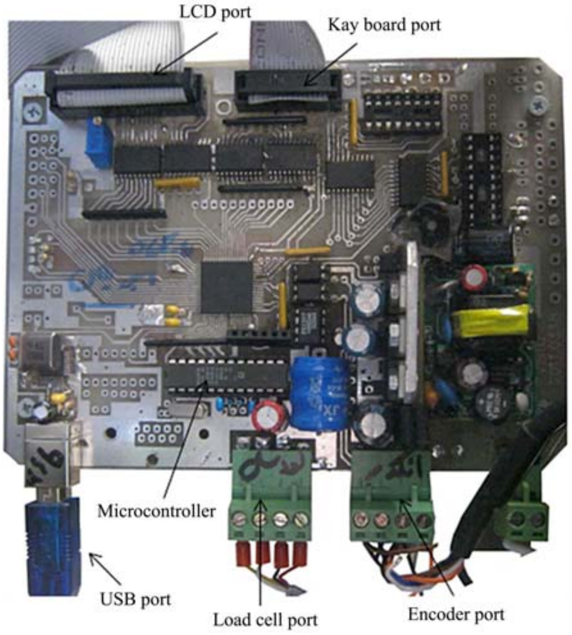


Figure 8 Data processing board

2.5 Technical specifications

The electronic parts and the transmission system are located inside the main frame (Figure 9).

The blades (vane) method is one of the popular and simple methods in labs because of its simplicity and ease.

The distribution of shear stress (τ) around the vane may be assumed to be uniform on the vertical edges of the vane blades but probably would be highly non-uniform on the top and the bottom surfaces. Thus the conventional interpretation of the test, given by the Equation (1) would be more conservative (Karmakar, 2005).

$$\tau = \frac{0.86M}{\pi D_v^3} \tag{1}$$

The yield stress of the material (σ_0) can be determined by Equation (2) (Tanjore, 2005);

$$\sigma_0 = \frac{2M}{\pi D_v^3}\left(\frac{H}{D_v} + \frac{1}{6}\right)^{-1} \tag{2}$$

where, M is the maximum torque (N.m); D_v and H are the vane dimensions (m) which are shown in Figure (1) (Tanjore, 2005).

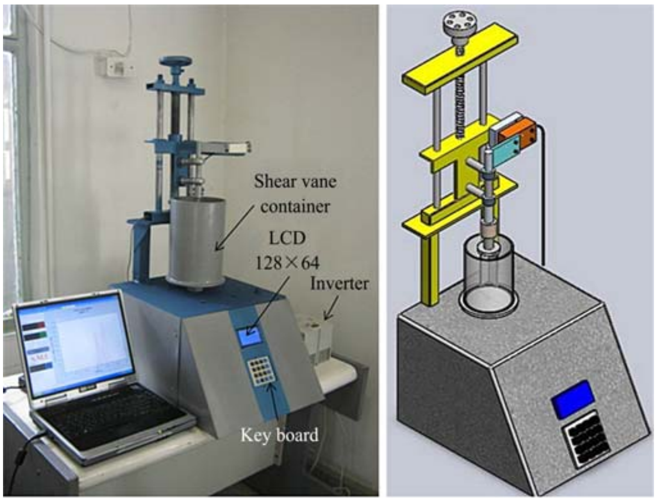


Figure 9 Constructed shear vane and the main components

2.6 Preparation of manure sample in shear vane container

The visco-plastic properties of cow manure were found and the experiments were done on cow manure at three moisture contents of 35%, 40% and 45%.

The prepared manures were transferred to the test container in three layers. Each layer was compacted by pounding a wooden block to the predetermined compaction level. Predetermined compaction levels were done at controlled conditions in order to have the same density for all experiments (Karmakar, 2005).

2.7 Test procedure

The vane was inserted into the material in the container by moving down the vertical displacement mechanism. The container was rotated at predetermined speeds of 0.1, 0.2 and 0.3 r min^{-1}. The speed was controlled by an inverter which was fixed at certain specific frequency (1 to 10 Hz). The response of cow manure to the shearing vane was registered for all predetermined manure conditions. A computer program was prepared for the data logger to record the torque, required to shear the material during the test.

3 Results and discussion

Visco-plastic properties of cow manure were determined in this research. Figure 10 shows the torque value during the shear test. The shear force, applied to the manure in the surrounding area of the vane, increased with the rotation of the container. The shear resistance of the manure against the vane increased until a rupture occurred in the materials and then decreased. The level of the torque which causes rupture of the materials was chosen as the maximum torque or peak point. The results of this section were similar to the rheological properties of soil measured by a shear vane (Karmakar, 2005).

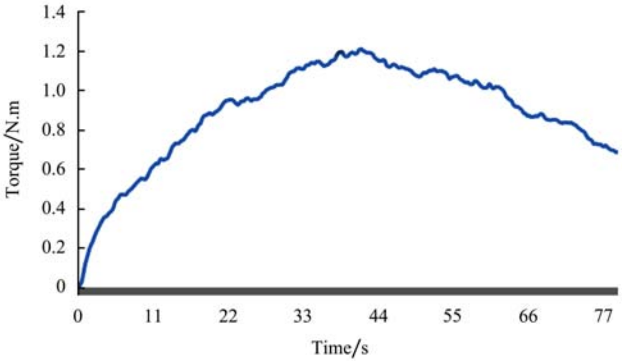


Figure 10 The variation of torque resulted by shear vane for cow manure at moisture content of 40% (w.b) and rotational speed of 0.1 r min^{-1}

The maximum torques were obtained at different rotational speeds and different levels of manure moisture content (Figure 11). The maximum torque or shear strength increased with the increasing rotational speed of the container. The results of this section were completely consistent with Karmakar's results. He compared the maximum shearing torques of soil at 17% moisture content (w.b) and at different speeds. He stated that the maximum torque increases with the increasing shear rate (Karmakar, 2005).

As was shown in Table 1, the highest peak for torque (2.25 N.m) was obtained at 35% moisture content and rotational speed of 0.1 r min^{-1} and the lowest peak (1.12 N.m) was achieved at 35% moisture content and rotational speed of 0.2 r min^{-1} (Figure 11).

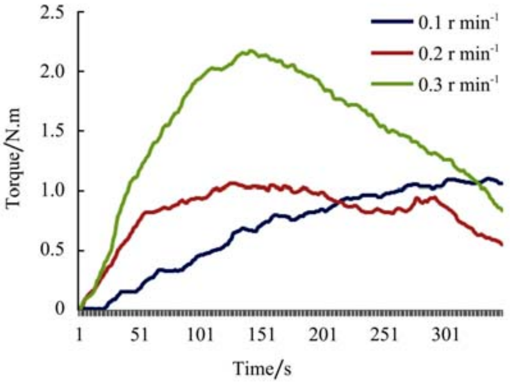
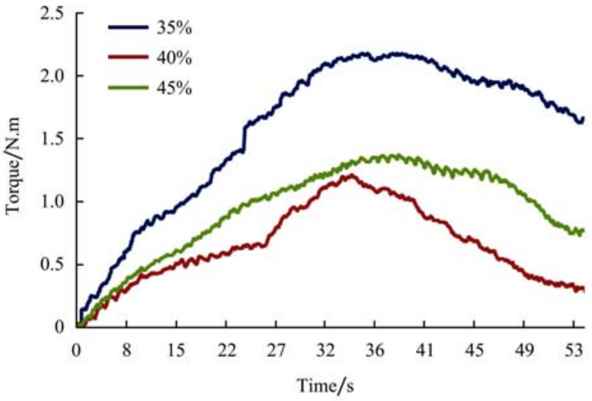


Figure 11 Changes of resulted torque by shear vane for cow manure at three levels of rotational speed and moisture content of 35%

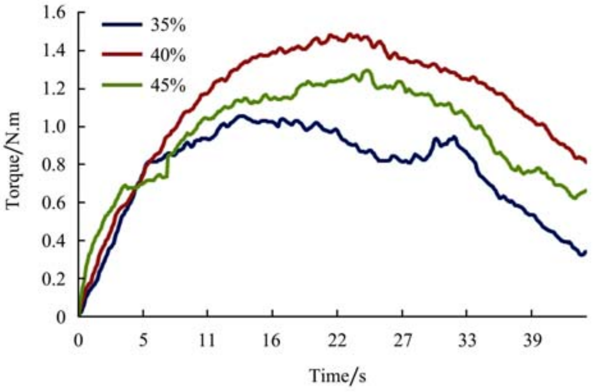
Table 1 Values of maximum torque, shear stress and yield stress in cow manure at three moisture and rotational speed of container levels

Rotation of container /r min^{-1}	Moisture content /%, w.b	M_{max} /N.m	Shear stress $_{max}$ (τ_{max}) /Pa	Yield stress $_{max}$ (σ_{max}) /Pa
0.1	35	2.25	4703.55	5054.03
	40	1.21	2518.15	2705.79
	45	1.45	3030.77	3256.61
0.2	35	1.12	2328.54	2502.05
	40	1.48	3084.73	3314.59
	45	1.29	2693.52	2894.23
0.3	35	2.17	4519.18	4855.93
	40	1.33	2776.71	2983.62
	45	1.47	3063.75	3292.04

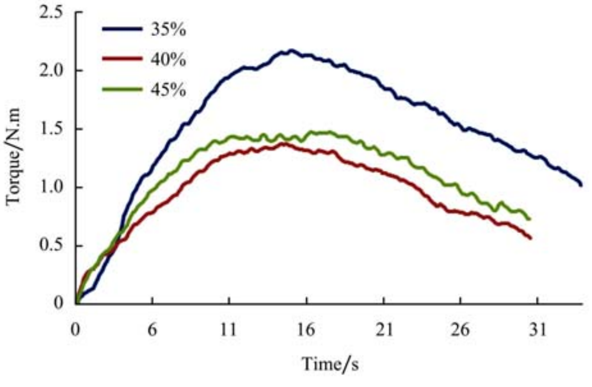
The results showed that the amount of shear stress and yield stress decreased with the increasing moisture content from 35% to 40% and rotational speed of 0.1 and 0.2 r min^{-1}. The maximum shear stress (4.70 kPa) and maximum yield stress (5.05 kPa) were obtained at 35% moisture content and rotational speed of 0.1 r min^{-1} while the lowest shear stress (2.32 kPa) and minimum yield stress (2.50 kPa) were obtained at 35% moisture content and rotational speed of 0.2 r min^{-1} (Table 1). This phenomenon can be found in water among manure particles and the friction between solid particles attributed to manure. The water molecules move more freely with the increasing of moisture content. This phenomenon may lead to decrease of solid-solid manure particles friction. The results in this section are consistent with results of Karmakar, which the yield stress decreased with increasing soil moisture up to 17% and then gradually increased up to 20% moisture content. This may be due to the increase in soil cohesion at higher moisture content.



a. 0.1 r min^{-1}



b. 0.2 r min^{-1}



c. 0.3 r min^{-1}

Figure 12 Changes of resulted torque by shear vane for cow manure at three moisture content levels and three rotational speeds

4 Conclusion

A shear vane was designed and built to determine the rheological properties of biomass materials. In the shear vane a bending-type loadcell was used instead of a torquemeter to determine the torque and the maximum shear stress of cow manure. The results showed that the maximum torque or shear strength increased with the increasing rotational speed. The maximum torque was obtained at 35% moisture content and a rotation speed of 0.1 r min^{-1} while the minimum torque (2.25 N.m) was obtained at 35% moisture content and rotational speed of 0.2 r min^{-1}. The results showed the highest shear stress (4.70 kPa) and maximum yield stress (5.05 kPa) at 35% moisture content and a rotational speed of 0.1 r min^{-1} and the minimum torque (1.12 N.m), minimum shear stress (2.32 kPa) and minimum yield stress (2.50 kPa) at 35% moisture content and a rotational speed of 0.2 r min^{-1}. The maximum torque (2.25 N.m), maximum shear stress (4.70 kPa) and maximum yield stress (5.05 kPa) were obtained at 35% moisture content and rotational speed of 0.1 r min^{-1} while the minimum torque (1.12 N.m), minimum shear stress (2.32 kPa) and minimum yield stress (2.50 kPa) were found at 35% moisture content and rotational speed of 0.2 r min^{-1}.

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