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Development of Motorized Rheometer for measure Cassava-pulp Yield Stress and Viscosity

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Abstract *— This research proposes a motorized high-torque rheometer to determine the yield stress and viscosity of cassava pulp. In the study, experiments are carried out with cassava pulp under variable moisture contents (79.49, 66.78, and 54.19%) and shear rates (12.37, 14.69, and 18.75 s^{-1}). To validate the rheometer, torque calibration is undertaken, and results are in good agreement with actual torque (R^2 = 0.9991). The experiments show that the yield stress and moisture content of cassava pulp are inversely correlated, while the yield stress is positively correlated with shear rates. Meanwhile, the moisture content and shear rate are inversely correlated with the viscosity of cassava pulp. Besides cassava pulp, the proposed rheometer is applicable to other materials with high torque whose properties are indeterminate using conventional low-torque rheometers.*

Keywords: *Rheometer, Cassava-pulp, Viscosity, Yield Stress*

I. INTRODUCTION

Cassava (Manihot esculenta) is a high-yielding root crop, and its root is a source for food and starch products. Cassava is a key ingredient of animal feed, and cassava pith is processed into tapioca for human consumption. The waste from cassava starch production (i.e., cassava pulp) is converted into ethanol and biomass [1-4].

In Thailand, the annual demand for fresh cassava tubers of the cassava starch industry stands at 10 million metric tons [5]. The cassava starch manufacture produces the solid waste called cassava pulp approximately 10 to 20% of the original cassava tuber weight [6-7]. Currently the waste from cassava starch production or cassava pulp is mostly processed into animal feed, ethanol, and biomass. In addition, cassava pulp from cassava starch production contains high moisture content (70-80% on average) [8-9] and thus a good source of microorganisms. The abundance of microbes shortens the storage life of cassava pulp.

Drying of cassava pulp to remove the moisture helps extend the storage life of cassava pulp. Indeed, the processing of cassava pulp involves mechanical machinery to transport the material to subsequent processing stages. Besides, the properties of the material are necessary in the design and fabrication of such machinery. However, the flow characteristics of cassava pulp, including yield stress and viscosity, are unknown. Additionally, the conventional viscometers and rheometers for food materials are unsuitable for cassava pulp [10]. As a result, this research proposes an economical high-torque vane rheometer to measure the yield stress and viscosity of cassava pulp. The proposed rheometer is experimented with cassava pulp under variable moisture contents and shear rate. Essentially, apart from cassava pulp, the rheometer is applicable to other materials whose properties are indeterminate using conventional rheometers.

II. MATERIALS AND METHODS

A. *Cassava pulp preparation*

Cassava pulp is from Korat Flour Industry Co., Ltd. in Thailand's north-eastern province of Nakhon Ratchasima. The moisture content of cassava pulp is determined by hot air oven method at 105°C for 24 h [11], and the initial moisture content is 79.49%. The cassava pulp is further oven-dried at 40°C to decrease the moisture content from 79.49 to 66.78 and 54.19% to investigate the effect of moisture content on cassava pulp yield stress and viscosity. The typical moisture content of cassava pulp from cassava starch production is 70-80% [8-9]. The moisture content of cassava pulp is calculated by equation (1)

$$M=\frac{w_i-w_f}{w_i}\times 100\% \tag{1}$$

where M is the moisture content of cassava-pulp (%, wet basis), w_i is the weight of cassava pulp before drying (g), and w_f is the weight of cassava pulp after drying (g).

The density of cassava pulp (cylindrical container), given the moisture content of 79.49 %, is 1,050 kg/m^3, independent of excavation depths of cassava pulp pile (i.e., 10, 50, and 100 cm).[12]

B. *The rheometer*

Fig. 1 illustrates the proposed motorized high-torque rheometer scheme to measure yield stress and viscosity. The rheometer scheme consists of a torque transducer for measuring and recording the torque (Hottinger Baldwin Messtechnik (HBM) T5/200 Nm); a four-blade vane; a steel container with a volume of 737 cm^3; 12V DC motor with a maximum speed of 100 rpm connected to the four-blade vane; DC power supply to manipulate the motor speed (Alimentatore Stabilizzato APR3010H); HBM spider 8.0 amplifier; and a computer with catman data acquisition (DAQ) software installed. The rheometer operates on the principle of torsional shear applied to the four-blade vane [13-14].

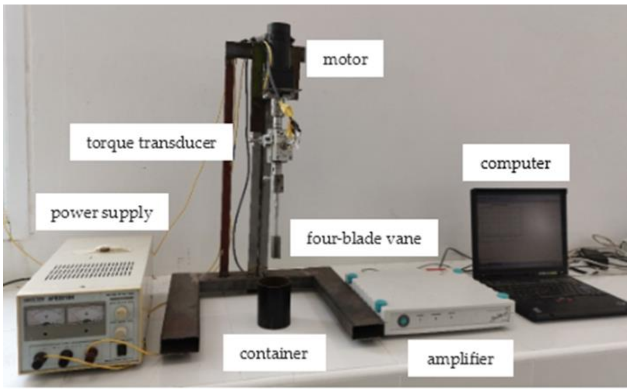

Fig. 1 The scheme of motorized rheometer

In this research, the shear blade method follows who determines the shear stress and viscosity of semi-solid foods using shear blade [15]. Fig. 2 illustrates the geometry of the four-blade vane in which the height of the vane is twice the diameter (2:1), in accordance with ASTM D4648/D4648M-16 [16]. The height and diameter of the vane are 50.8 mm and 25.4 mm. The four-blade vane is conventionally used for processing of agricultural products [17-18].

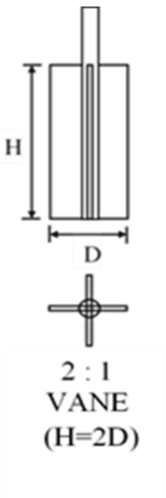

Fig. 2 Geometry of four-blade vane where H and D denote the height and diameter of the vane [16]

C. Experimental methods

a) Torque transducer calibration

In calibration, forces are applied to the torque transducer, and results in millivoltage (mV) are measured by catman DAQ. The electrical voltages are converted into torque to establish a relationship between electrical voltage and torque. The resulting torque is subsequently compared against theoretical torque. In this research, the force (F) is varied between 0.09 – 1.9 N and the length of the shaft (L) remains constant (0.5 m). Theoretically, the torque is calculated by equation (2) [19]

$$T = F \times L \qquad (2)$$

where T is the torque (N.m), F is the force (N), and L is the length of the perpendicular force

b) Yield stress measurement

In shear stress measurement, the cassava pulp with 79.49, 66.78, and 54.19% moisture content are individually filled into 737 cm^3 steel containers, given the density of 1,050 kg/m^3. The motor rotational speed is varied between 64, 76, and 97 rpm, corresponding to the power supply of 7, 9, and 11 V. The experiments are carried out in triplicate and results averaged. The yield stress is calculated by equation (3) [20]

$$\tau_m = \frac{T_m}{K} \qquad (3)$$

where τ_m is the yield stress (N/m^2), T_m is the maximum torque (N.m), and K is the blade vane constant (m^3).

Assuming that the distribution of shear stress is uniform throughout vane blades, K is thus calculated by equation (4)

$$K = \frac{\pi D^2 H}{2 \times 10^9}\left[1 + \frac{D}{3H}\right] \qquad (4)$$

where D is the diameter of the vane (mm) and H is height of the vane (mm).

c) Viscosity measurement

The apparent viscosity of cassava pulp with different moisture contents (79.49, 66.78, and 54.19%) is a function of yield stress and shear rate. In [21-22], the viscosity of food semi-solids, solids, and suspensions are determined by vane rheometric technology. The apparent viscosity is calculated by equation (5) [23]

$$\eta = \frac{\tau_m}{\dot{\gamma}} \qquad (5)$$

where η is the apparent viscosity (Pa.s) and τ_m is the shear rate (s^{-1}) which is calculated by assuming that the average shear rate of the vane is directly proportional to rotational speed, as expressed in equation (6) [20,23]

$$\dot{\gamma} = k_s \frac{N}{60} \qquad (6)$$

where N is the rotational speed (rpm) and k_s is the constant of vane (11.6/rev).

III. RESULTS AND DISCUSSION

A. Calibration of torque transducer

The linear relationship between electrical voltage and torque of the transducer, given the force of 0.09 – 1.9 N and the shaft length of 0.5 m expressed in equation (7), where T is torque (N.m) and V is the voltage of the torque transducer (mV).

$$T = 99.129V - 0.0099 \qquad (7)$$

The linear coefficients are incorporated into the catman DAQ program to convert the electric voltage into torque and compared against actual torque, as shown in Fig. 3.

The measured torque is almost identical to the actual, with R^2 of 0.9991.

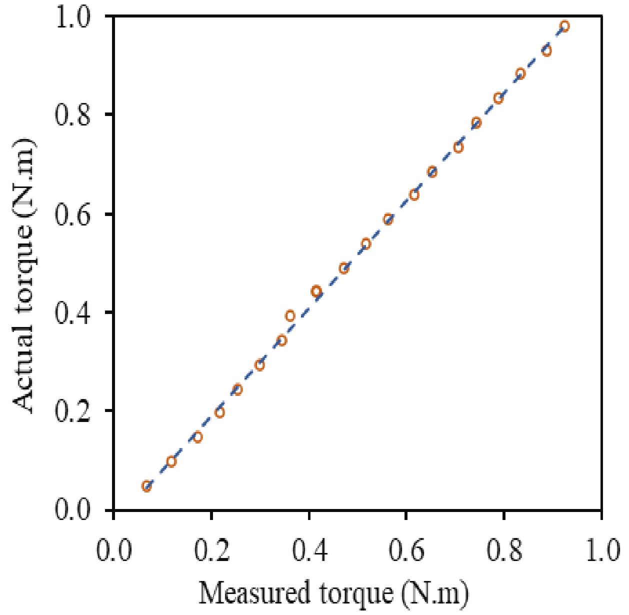

Fig.3 Relation between the measured torque and actual torque

Fig. 4 (a)-(c) respectively illustrate the torque of cassava pulp with different moisture contents (79.49, 66.78, and 54.19%) and the density of 1,050 kg/m^3, given the rotational speeds of 64, 76, and 97 rpm. In the figures, once the maximum torque is reached, the torque of cassava pulp steadily declines and subsequently becomes relatively constant, indicating the complete destruction of cassava pulp [24-25]. Table 1 tabulates the maximum torque of cassava pulp with different moisture contents (79.49%, 66.78%, and 54.19%) and rotational speeds (64, 76, and 97 rpm) using the rheometer. The torque is inversely correlated with the moisture content and positively correlated with the rotational speed.

Table 1. The maximum torque of cassava pulp under different moisture contents and rotational speeds using the proposed vane rheometer scheme

Rotational speed (rpm)	Moisture content (wet basis)		
	79.49%	66.78%	54.19%
	Torque (N.m)		
64	0.24	0.28	0.28
76	0.23	0.31	0.34
97	0.20	0.38	0.42

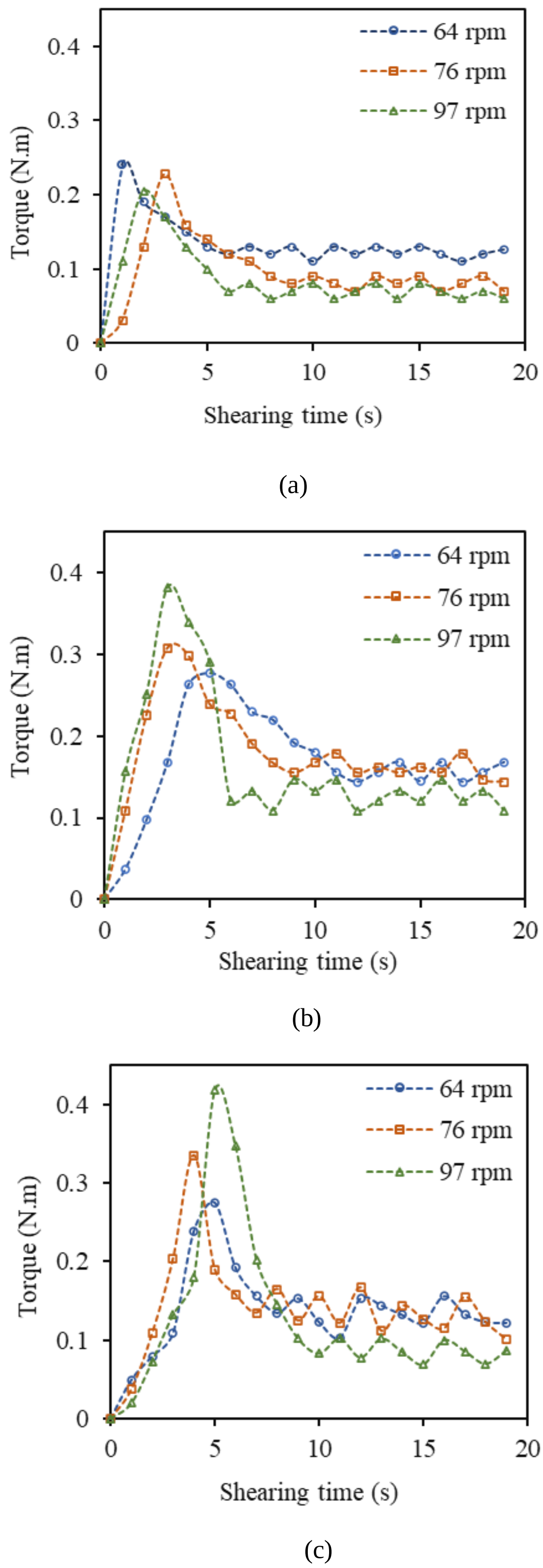

Fig. 4 Torque of cassava pulp relative to shearing time under different moisture contents: (a) 79.49%, (b) 66.78%, (c) 54.19%

B. Effect of moisture content on yield stress

Fig. 5 depicts the yield stress of cassava pulp under different moisture contents and shear rates. The shear rates of 64, 76, and 97 rpm rotational speeds are 12.37, 14.69, and 18.75 s^{-1}. The yield stress is inversely correlated to the moisture content. In other words, the yield stress decreases with increase in moisture content. The phenomenon is attributable to lower friction between cassava pulp particles as the cassava pulp moisture increases, resulting in lower yield stress [26].

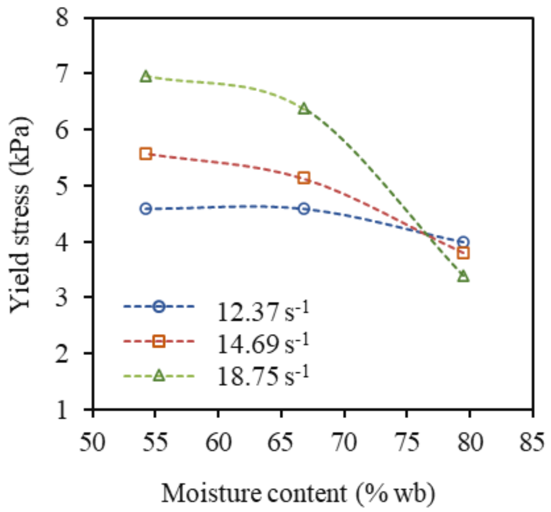

Fig. 5 Effect of moisture content of cassava pulp on yield stress given the shear rates.

In Fig. 5, given 79.49% moisture content, the variation in shear rates has a small effect on the yield stress. The yield stress are 3,996.33, 3,798.18, and 3,401.87 Pa for 12.37, 14.69, and 18.75 s^{-1}. The small difference in yield stress is attributable to the near-complete destruction of cassava pulp particles. With the moisture content of 66.78 and 54.19%, the shear rate has a significant impact on the yield stress. This is due to higher friction between cassava pulp particles as material moisture is reduced, thus resulting in higher yield stress.

C. Effect of moisture content on viscosity

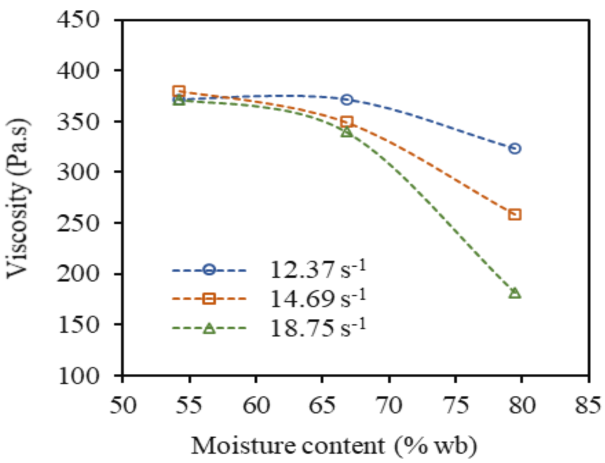

Fig.6 Effect of moisture content of cassava pulp on viscosity given the shear rate.

Fig. 6 compares the viscosity of cassava pulp with different moisture contents and shear rates. The viscosity is inversely correlated to the moisture content. The finding is attributable to increased voids between cassava pulp particles as the moisture increases, reducing the adhesion between cassava pulp particles. The lower adhesion contributes to lower viscosity of cassava pulp [27]. In addition, the effect of variable shear rates on viscosity is more pronounced with increase in cassava-pulp moisture content. Specifically, with 54.19% moisture content, the viscosity of cassava pulp are almost identical (371.12, 379.92, and 371.66 Pa.s for 12.37, 14.69, and 18.75 s^{-1}). On the other hand, with 79.49%, the differences in viscosity become very large (323, 258, and 181 Pa.s for 12.37, 14.69, and 18.75 s^{-1}).

D. Effect of shear rate on yield stress

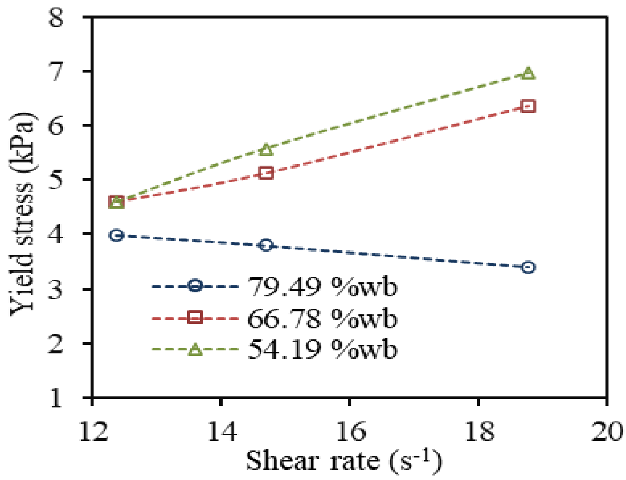

Fig.7 Effect of shear rate on yield stress of cassava pulp under different moisture contents

In the analysis, the rotational speeds are first converted into shear rates using equation (6). Fig. 7 illustrates the effect of shear rate on yield stress under different cassava-pulp moisture contents. At 79.49%, the yield stress decreases with increase in the shear rate. This is attributable to lower frictions between cassava pulp particles as larger numbers of water molecules take up the voids between particles with increased moisture content. Under 66.78 and 54.19%, the yield stress increases with increase in shear rate due to stronger adhesion between cassava pulp particles, resulting in higher yield stress [28].

E. Effect of shear rate on viscosity

Fig. 8 illustrates the effect of shear rate on viscosity under different cassava-pulp moisture contents. The viscosity of cassava pulp decreases as the shear rate increases [29] due to the destruction of cassava pulp structures by hydrodynamic force and orientation of cassava pulp in the same direction as the rotation [26]. The highest viscosity of cassava pulp (379.92 Pa.s) is reached at the shear rate of 14.69 s-1 and 54.19% of moisture content.

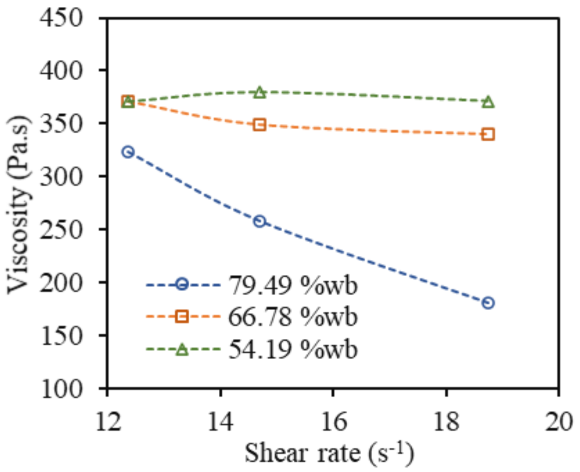

Fig. 8 Effect of shear rate on viscosity of cassava pulp under different moisture contents

Table 2 tabulates the yield stress and viscosity of cassava pulp under different moisture contents (79.49, 66.78, and 54.19%) and shear rate (12.37, 14.69, and 18.75 s^{-1}) using the proposed rheometer. At 54.19% of moisture content, the highest yield stress of 6,968.66 Pa and the maximum viscosity of 379.92 Pa.s are achieved at 18.75 and 14.69 s^{-1} shear rate, respectively. The numerical results (i.e., 6,968.66 Pa and 379.92 Pa.s) are the design criteria of machinery for cassava pulp processing.

Table 2. Yield stress and viscosity of cassava pulp under variable moisture contents and shear rate

Shear rate (s^{-1})	Moisture content (wet basis)					
	79.49%		66.78%		54.19%	
	Yield stress (Pa)	Viscosity (Pa.s)	Yield stress (Pa)	Viscosity (Pa.s)	Yield stress (Pa)	Viscosity (Pa.s)
12.37	3,996.33	323.07	4,590.80	371.12	4,590.80	371.12
14.69	3,798.18	258.16	5,129.78	349.20	5,581.24	379.92
18.75	3,401.87	181.43	6,374.19	339.96	6,968.66	371.66

IV. CONCLUSIONS

This research proposes a motorized rheometer to measure the yield stress and viscosity of cassava pulp. In the study, the rheometer is experimented with the moisture content of cassava pulp of 79.49, 66.78, and 54.19% and the shear rate of 12.37, 14.69, and 18.75 s^{-1}, given the cassava pulp density of 1,050 kg/m^3. To validate the rheometer scheme, torque calibration is carried out and results are in good agreement with theoretical torque (R^2 =0.9991). The experiments reveal that the yield stress of cassava pulp is inversely correlated with moisture content and positively correlated with shear rate. The highest yield stress of 6,968.66 Pa is achieved under 54.19% of moisture content and the shear rate of 18.75 s^{-1}. Meanwhile, the moisture content and shear rate are inversely correlated with the viscosity of cassava pulp, with the maximum cassava pulp viscosity of 379.92 Pa.s under 54.19% of moisture content and the shear rate of 14.69 s^{-1}. In addition to cassava pulp, the proposed vane rheometer scheme is applicable to many other materials whose properties are indeterminate using conventional low-torque rheometers.

V. ACKNOWLEDGMENTS

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