Flow-specific physical properties of coconut flours

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A b s t r a c t. Coconut milk residue and virgin coconut oil cake are important co-products of virgin coconut oil that are used in the animal feed industry. Flour from these products has a number of potential human health benefits and can be used in different food formulations. The objective of this study was to find out the flow-specific physical properties of coconut flours at three moisture levels. Coconut milk residue flour with 4.53 to 8.18% moisture content (w.b.) had bulk density and tapped density of 317.37 to 312.65 and 371.44 to 377.23 kg m^{-3}, respectively; the corresponding values for virgin coconut oil cake flour with 3.85 to 7.98% moisture content (wet basis) were 611.22 to 608.68 and 663.55 to 672.93 kg m^{-3}, respectively. The compressibility index and Hausner ratio increased with moisture. The angle of repose increased with moisture and ranged from 34.12 to 36.20 and 21.07 to 23.82° for coconut milk residue flour and virgin coconut oil cake flour, respectively. The coefficient of static and rolling friction increased with moisture for all test surfaces, with the plywood offering more resistance to flow than other test surfaces. The results of this study will be helpful in designing handling, flow, and processing systems for coconut milk residue and virgin coconut oil cake flours.

K e y w o r d s: coconut flours, bulk density, tap density, friction coefficient, angle of repose

INTRODUCTION

Virgin coconut oil (VCO) is in high demand worldwide because of its health benefits. Various cold and hot processes are used for the extraction of VCO from the fresh coconut kernel (Arumuganathan *et al*., 2011). Coconut milk residue and VCO cake are the two important co-products in VCO production, and both are ground to a meal used in animal feed. In humans, these granular co-products provide a number of health benefits related to reducing the risks of coronary heart diseases, colon cancer, and diabetes because of their high dietary fibre content (Trinidad *et al*., 2007). Consumption of high-fibre coconut meal products has been shown to increase faecal bulk and lower the serum cholesterol (Gunathilake *et al*., 2009).

A combination of physical and chemical properties of the material, environmental conditions, equipment used in handling and transport, and storage time influences the flow of granular material (Prescott and Barnum, 2000). Some of the specific factors that affect flowability include moisture content, fat content, particle size, shape, and density (Fitzpatrick *et al*., 2004; Morr, 1990; Perez and Flores, 1997). The handling, storage, and flow of any particulate material are important for the agricultural, food, chemical, ceramic, pharmaceutical, and metallurgical bulk solids and powder processing industries. Flow is defined as the relative movement of bulk particles among neighbouring particles or along a container wall surface (Peleg, 1977). Flow characteristics are important because they dictate the ease of conveying, blending, and packaging during bulk material handling and processing. Characterizing the flow behaviour of bulk granular materials accurately is crucial to ensuring steady and reliable flow (Kamath *et al*., 1994).

Moisture plays a key role in determining the flow properties of a material. Most organic materials are hygroscopic, meaning they gain or lose moisture when exposed to various humidity temperature conditions, leading to physical and chemical changes. Hygroscopicity alters cohesiveness, chiefly through inter-particle liquid bridge formation (Johanson, 1978). As the moisture content of a powder increases, adhesion (Craik and Miller, 1958) and

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cohesion (Moreyra and Peleg, 1981) tend to increase. Even a small change in moisture content can substantially affect the frictional properties of material (Marinelli and Carson, 1992). In the past few decades, many researchers have examined the effects of moisture content on physical and flow properties of granular solids and powders (Athmaselvi *et al*., 2014; Duffy and Puri, 1994; Hollenbach *et al*., 1983; Yan and Barbosa-Canovas, 1997).

The co-products of the coconut flour industry are relatively new, so data and understanding of the properties that influence the flowability of coconut milk residue and VCO cake flours are lacking. This knowledge is critical to the successful use of coconut-based flours by the bakery, confectionery, extrusion, and livestock feed industries. Therefore, the objective of this study was to examine the effects of moisture content on the flow-specific physical characteristics of coconut-based flours. Keeping in mind that the nutritional and physical properties of coconut flours vary, the effects of three moisture contents (4.53, 6.23, and 8.18% w.b. for coconut milk residue flour and 3.85, 6.01, and 7.98% w.b. for VCO cake flour) on flow-specific physical properties of flours were investigated.

MATERIALS AND METHODS

Mature 11-month-old West Coast Tall variety coconut was used in this study for the preparation of coconut flours. The coconut milk residue flour was prepared by milling the dried coconut milk residue obtained during the extraction of coconut milk. The VCO cake flour was made by milling the dried VCO cake obtained during VCO extraction. The milling of coconut milk residue and VCO cake was carried out using a 50 kg h⁻¹ capacity pulveriser (Pilotsmith, Thrissur, Kerala, India) using a 0.63 mm mesh screen. The proximate composition, total dietary fibres, free fatty acid, and peroxide values of the samples were determined using AACC standard methods (AACC, 2000). Particle size distribution was measured using the ASABE S319.3 method (ASABE, 2003) using a Ro-Tap sieve shaker (RX-29, W.S.Tyler, Mentor, OH). This involved shaking 100 g samples on the set of sieves for 15 min. After sieving, the geometric mean diameter of the flour particles was determined from the mass retained on each sieve using the ASABE method.

In general, coconut flours are stored and transported at low moisture content and agglomerate above 8% w.b. moisture content. To study the moisture effect on flow properties, samples with higher moisture contents were prepared by adding a calculated amount of water based on their dry matter content (Kingsly and Ileleji, 2009). Distilled water was sprayed uniformly onto the flour and thoroughly mixed in a flour-conditioning bin at the Kansas State University Department of Grain Science and Industry in Manhattan, KS, USA. Water was added incrementally to avoid agglomeration. The moisture-conditioned samples were then stored in polypropylene bags (thickness – 100 μm, water

vapour transmission rate – 2.31 g m⁻² day⁻¹, oxygen transmission rate – 1169 cc m⁻² day⁻¹ atm⁻¹) at 4°C for 72 h before the experiments. After conditioning, the moisture contents were 4.53, 6.23, and 8.18% w.b. and 3.85, 6.01, and 7.98% w.b. for milk residue and VCO cake flours, respectively, as per the AACC standard method (AACC, 2000). The water activity of flours at the corresponding moisture level was determined using an automated water activity meter (M/s. Aqua lab, USA) and found as 0.28, 0.34, and 0.40 for milk residue flours and 0.23, 0.28, and 0.38 for VCO cake flours. Each property test was conducted in triplicate, and mean values with standard deviation at 5% significance levels were reported. All statistical analyses (analysis of variance, standard deviation, and a multiple comparison procedure) were performed using the statistical software package of Microsoft Excel 2007 (Microsoft Corporation, Redmond, WA, USA).

Bulk density depends on particle size, moisture, and chemical composition, but also on handling and processing operations. A Winchester cup arrangement (Seedburo Equipment Company, IL, USA) was used to estimate the bulk density of the coconut flours.

The autotap density analyser (Quantachrome instruments, FL, USA) was used for tapped density measurement. A cylinder of known volume was filled completely with the sample and tapped 750 times (260 taps per minute). The tapped density was calculated from the final weight and volume of the sample after tapping.

The compressibility index of coconut flours was calculated using the following equation (Kingsly *et al*., 2010):

$$C = 100 \frac{T - B}{T}, \qquad (1)$$

where: C is the compressibility index, T is the tapped density (kg m⁻³), and B is the bulk density (kg m⁻³). The greater the compressibility of a bulk solid, the less flowable it is. Compressibility of 25% is the dividing point between free-flowing and non-flowing powders (Carr, 1965). Hausner ratio (H) is used as an internal friction index for cohesive powders (Guo *et al*., 1985; Malave *et al*., 1985) and is the ratio between tapped and bulk density.

$$H = \frac{T}{B}. \qquad (2)$$

The angle of repose corresponds qualitatively to the flow properties of a material and is a direct indication of potential flowability (Carr, 1965). In this study, the method suggested by Balakrishnan *et al*. (2011) was used to quantify the effects of moisture content on the angle of repose of coconut flours.

The coefficient of static friction was determined on three surfaces: plywood, acrylic plastic and steel sheet. A procedure similar to the one described by Garnayak *et al*. (2008) was used in this study to determine the coefficient of rolling friction between the particle and the wall. A tilting

platform setup was fabricated and used for this purpose. The sample was poured onto the same surfaces used for the static friction coefficient test such that it formed an inverted cone. Using the attached manually driven screw, the inclination of the platform was slowly increased until the sample began to roll. The angle of inclination at this point was determined using the height of the platform from the base and the base length. The coefficient of rolling friction was calculated as the tangent of the angle of inclination.

RESULTS AND DISCUSSION

The crude protein and moisture contents of VCO cake flour samples were higher than those of coconut milk residue flour under as-is conditions (Table 1). The crude fat content of coconut milk residue flour is significantly higher than for VCO cake flour, which affects its cohesiveness and flowability (Fitzpatrick et al., 2004). The fibre content of coconut milk residue was significantly higher than that of VCO cake flour, whereas VCO cake flour was richer in ash, free fatty acid, and peroxide value than coconut milk residue flour.

Coconut milk residue and VCO cake flour had similar particle size distribution (Fig. 1), but VCO cake flour had more larger-sized particles. This result could be related to the presence of a higher amount of protein that aided in agglomeration of VCO cake flour powders (Emami and Tabil, 2008). The skewed particle size distribution of coconut flours is typical for naturally occurring particle populations (Rhodes, 1998). A similar response has been reported for alfalfa, wheat straw, barley straw, and corn stover grinds (Mani et al., 2004; Yang et al., 1996).The geometric mean diameter of coconut milk residue flour and VCO cake flour were 524.8±10.7 and 594.6±5.6 µm, respectively. VCO cake flour is expected to have slightly

T a b l e 1. Chemical composition of coconut flours

Parameters	Coconut milk residue flour	VCO cake flour	F-value	p-value
Crude protein (% N x 6.30)	5.29±0.07a	20.12±0.08b	60771.17**	1.62 10^{-09}
Moisture (%)	2.86±0.19a	3.12±0.10a	4.75ns	0.09
Crude fat (%)	49.24±0.65a	35.57±0.19b	1218.53**	4.02 10^{-6}
Crude fiber (%)	25.51±0.65a	3.80±1.74b	409.59**	3.52 10^{-5}
Ash (%)	0.93±0.01a	6.08±0.08b	11131.20**	4.84 10^{-8}
Total dietary fiber (%)	46.50±0.35a	12.75±0.31b	15507.74**	2.49 10^{-8}
Free fatty acids (%)	1.20±0.02a	1.79±0.06b	278.41**	7.56 10^{-5}
Peroxide value (mEq kg^{-1})	0.25±0.01a	0.57±0.06b	101.09**	5.5 10^{-4}

The values after ±are standard deviation at $\alpha = 0.05$. Values with the same superscripts in the same row for a given property are not significantly different, and values followed by different superscripts are significant at $\alpha = 0.05$ level, ns – not significant. Significant at: *$\alpha = 0.05$, **$\alpha = 0.01$ level.
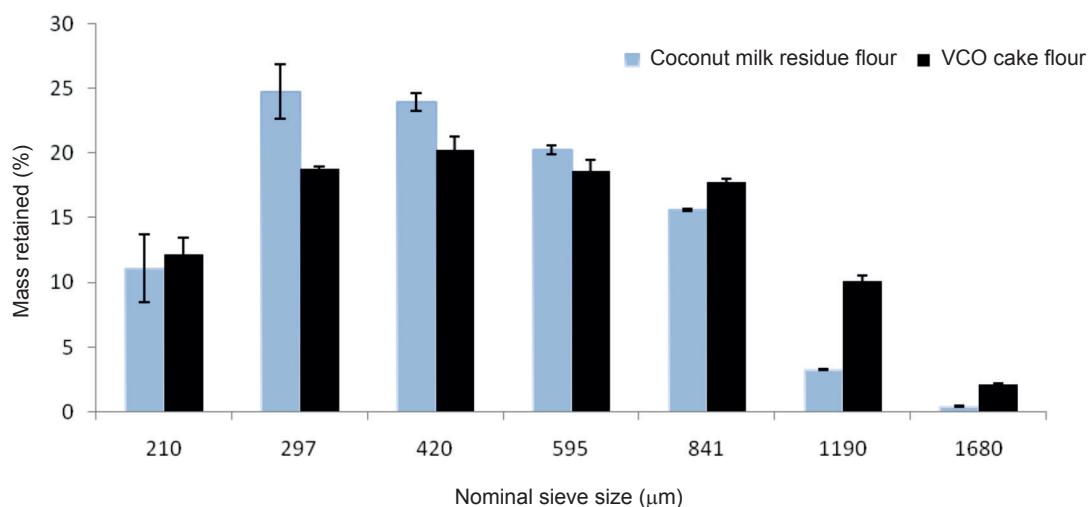

Fig. 1. Particle size distribution of coconut milk residue flour and VCO cake flour.

T a b l e 2. Effects of moisture content on flow indicators of coconut milk residue flour

Property	Moisture content (% w.b.)			F-value	p-value
	4.53	6.23	8.18		
Bulk density (kg m^{-3})	317.37±5.56a	315.90±4.79a	312.65±1.34a	0.95ns	0.44
Tapped density (kg m^{-3})	371.44±7.00a	377.23±5.68a	373.76±1.88a	0.90ns	0.45
Compressibility index	14.55± 0.19a	16.26±0.10b	16.35±0.18b	114.66**	1.66 10^{-5}
Hausner ratio	1.17±0.00a	1.19±0.00b	1.20±0.00b	113.81**	1.69 10^{-5}
Angle of repose (°)	34.12±0.61a	35.40±0.65a	36.20±1.05a	5.24*	0.03

Explanations as in Table 1.

T a b l e 3. Effects of moisture content on flow indicators of VCO cake flour

Property	Moisture content (% w.b.)			F-value	p-value
	3.85	6.01	7.98		
Bulk density (kg m^{-3})	611.22±2.24a	609.19±1.24a	608.68±0.48a	2.39ns	0.17
Tapped density (kg m^{-3})	663.55±4.12a	668.33±1.66ab	672.93±0.68b	9.81*	0.01
Compressibility index	7.89±0.31a	8.85±0.06b	9.55±0.02c	61.33**	1.01 10^{-4}
Hausner ratio	1.09±0.00a	1.10±0.00b	1.11±0.00c	63.47**	9.20 10^{-5}
Angle of repose (°)	21.07±1.50a	22.95±0.64a	23.82±1.25a	4.20ns	0.07

Explanations as in Table 1.

better flowability because larger particle size results in decreased surface area per unit of flour mass and reduced cohesion due to decreased frictional forces.

The decrease in bulk density of coconut milk residue flour and VCO cake flour was not significant with the increase in moisture content (Tables 2 and 3). The tapped density of VCO cake flour, however, followed an increasing trend with moisture, whereas there was no definite tapped density trend for coconut milk residue flour. Formation of an open-bed structure supported by inter-particle forces might have resulted in decreased bulk density of both flours with increased moisture (Fitzpatrick *et al*., 2004; Peleg and Mannhei, 1973). Bulk density and tapped density of VCO cake flour was greater than for coconut milk residue flour. Increased moisture content resulted in 0.46 to 1.49% and 0.33 to 0.42% decreases in bulk density of coconut milk residue flour and VCO cake flour, respectively. This decrease occurred mainly because of the increased volume of powders rather than an increase in mass. Moisture causes swelling, which means that the same mass of material occupies more volume, thus decreasing the bulk density. Similar to the findings reported here, a decreasing bulk density trend was reported by Guan and Zhang (2009) for wheat flours and Ganesan *et al*. (2008) for distillers dried grains with solubles (DDGS).

Moisture content had a significant effect on the compressibility index and Hausner ratio of coconut flours (Tables 2 and 3). In general, materials with compressibility index values lower than 25 are categorized as 'good flowable materials' but those greater than 25 are categorized as 'less flowable materials' (Carr, 1965). In this study, both types of flours had compressibility index values lower than 25, suggesting that neither should have flow problems at the moisture content range studied. Flowability does not depend on one parameter, however, and compressibility index and Hausner ratio are flow indicators; although the compressibility index and Hausner ratio are within 'flowable' limits, other factors could affect the bulk flow of these powders. Smaller particle size tends to reduce flowability, because the particle surface area per unit mass increases as particle size decreases, providing a greater surface area for surface cohesive forces to interact and resulting in cohesive flow. Ganesan *et al*. (2008) also observed a similar trend of increasing the DDGS compressibility with moisture content. The increase in Hausner ratio and compressibility index with increased moisture content is consistent with the studies of Chang *et al*. (1998) and Emery *et al*. (2009) for food and pharmaceutical powders, respectively.
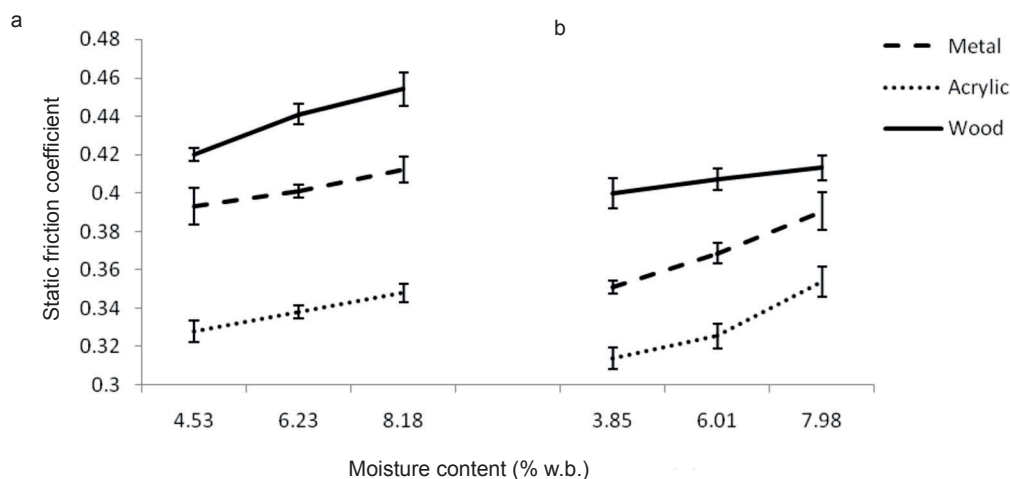
Fig. 2. Static friction coefficient of: a – coconut milk residue flour and b – VCO cake flour.
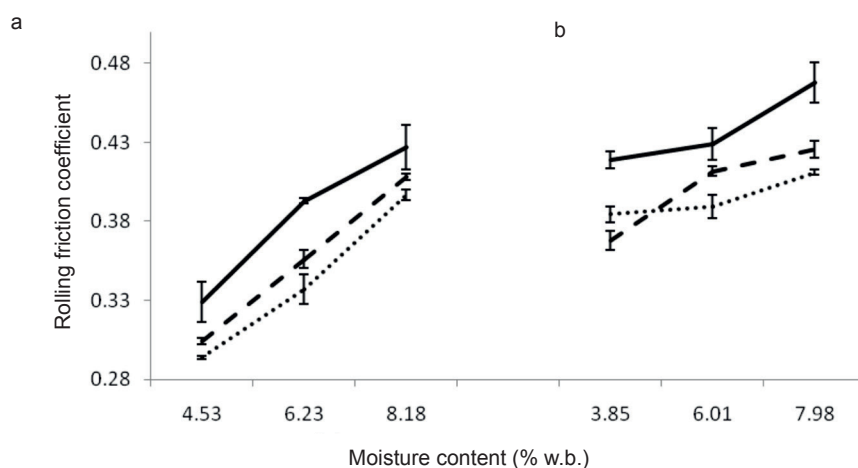

Fig. 3. Rolling friction coefficient of: a – coconut milk residue flour and b – VCO cake flour. Explanations as on Fig. 2.

The angle of repose of coconut flours increased linearly with increased moisture content (Tables 2 and 3), but the increase was not statistically significant. The angle of repose for coconut milk residue flour was higher than for the VCO cake flour. With high fat content and smaller particles, coconut milk residue flours had higher cohesion that resulted in increased angle of repose values. According to the classification by Carr, powders with an angle of repose less than 40° should flow easily, but those with greater than 45° will probably not flow well (Carr, 1965). Thus, the angle of repose for each type of coconut flour falls in the easy-flow classification. A similar trend was also reported by Kingsly *et al*. (2006) for anardana, Balasubramanian *et al*. (2012) for coriander seeds, and Emery *et al*. (2009) for Aspartame and HPMC pharmaceutical powders.

The static friction coefficient of coconut flours increased linearly with an increase in moisture content on all the tested surfaces (Fig. 2). The friction coefficient of plywood was found to be higher than that of steel and acrylic plastic sheet. A similar observation was reported by Subramanian and Visvanathan (2007) for millet flours and Barnwal

et al. (2014) for cryogenic and ambient ground turmeric. The lower value of the static coefficient of friction in the case of the acrylic plastic sheet was due to the smooth and polished surface compared with the other surfaces tested. Statistical results showed that the material surface had a more pronounced effect than moisture content on static friction (Table 4).

The results shown in Fig. 3 reveal a linear increase in rolling friction with moisture content for all contact surfaces. The increased rolling friction coefficient at higher moisture contents may be associated with adhesive force on the surface of contact. Plywood offered more rolling friction than the other acrylic and steel surfaces. The wall surface had a more significant influence than moisture content in rolling friction (Table 4). Plywood was reported to offer higher friction for pepper seed, jatropha seed, pigeon pea, gram, canola meal, and neem nut, and the coefficient of friction increased with moisture content (Alibas and Koksal, 2015; Dutta *et al*., 1988; Garnayak *et al*., 2008; Kulkelko *et al*., 1988; Shepherd and Bhardwaj, 1986; Visvanathan *et al*., 1996).

T a b l e 4. Statistical analysis and significance of test variables

Variables	F-value	p-value	F critical
Static friction coefficient			
Test surface	282.34**	2.56 10^{-14}	3.55
Moisture content	47.78**	6.32 10^{-8}	3.55
Test surface x moisture	4.37*	0.012146	2.93
Rolling friction coefficient			
Test surface	100.34**	1.74 10^{-10}	3.55
Moisture content	90.60**	4.02 10^{-10}	3.55
Test surface x moisture	8.81**	4.02 10^{-4}	2.93

Significant at: *$p < 0.05$, **$p < 0.01$.

CONCLUSIONS

1. The geometric mean diameter of coconut milk residue flour and virgin coconut oil cake flour were 524.8±10.7 and 594.6±5.6 µm, respectively.

2. Bulk density of both flours decreased with moisture content. The values of bulk and tapped density were higher for virgin coconut oil cake flour than for coconut milk residue flour.

3. In comparison, the compressibility index and angle of repose of coconut milk residue flour was higher than virgin coconut oil cake flour, indicating relatively poor flow behaviour of coconut milk residue flour.

4. Among the three test surfaces (plywood, acrylic plastic and steel sheet), plywood exhibited a higher coefficient of static and rolling friction.

5. All flow-related physical properties (compressibility index, Hausner ratio, angle of repose, coefficient of static and rolling friction) showed an increasing trend with moisture content.

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