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Moisture Dependent Dynamic Flow Properties of Coconut Flours

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Abstract: The dynamic flow properties of two important coproducts of virgin coconut oil (VCO) i. e. coconut milk residue flour (MRF) and VCO cake flour (CF) were studied. The basic flowability energy of CF was higher than MRF and increased with moisture content. The change in compressibility and shear stress, with applied normal stress and moisture content, indicated that these powders are highly cohesive. For both flours, the energy required to make the powder flow increased with moisture at all experimental air velocity. Moisture did not significantly influence the cohesion and unconfined yield strength of MRF, whereas for CF there was significant effect due to the presence of moisture. The wall friction angle of both the flours increased significantly with moisture and decreased with applied normal stress. The results from this study indicated that, both CF and MRF at around 4.00 % moisture content had better flow characteristics than at higher moisture levels.

Keywords: coconut flour, flow properties, cohesion, shear properties

1 Introduction

Coconut flours are the coproducts from coconut milk and virgin coconut oil production. For its health benefits, virgin coconut oil (VCO) from fresh coconut kernel has emerged as a highly demanded product throughout the world. Conversion of coconut to VCO results in two major coproducts namely the coconut milk residue flour (MRF) and VCO cake flour (CF). The production process of these coproducts is explained in detail by Bawalan [1]. Dried coconut flours are rich in protein, fat, and dietary fibers [2]. Coconut flours have been found to have health benefits for preventing coronary heart diseases, colon cancer, and diabetes [3]. It has also been reported that consumption of high fiber coconut meal products increases fecal bulk and lowers the serum cholesterol [4]. These flours can be utilized in functional and health foods in the form of extrudates, bakery, and confectionery products. In addition, coconut flours have the scope of utilization in animal feeds, pharmaceuticals, and in cosmetics [5].

The processing of coconut flours into different products generally involves unit operations such as fluidization, pneumatic conveying, blending, grinding, compaction, and storage in bins. Reliable flow of these granular materials is extremely important because it could affect the final product quality and the efficiency of the processes. Poor flow leads to wastage, machinery maintenance problems and downtime, with associated costs [6]. As a consequence, flow characterization of powders is often required for reliable equipment design and consistent process flow. Several techniques have been reported for quantifying the properties of granular material that could be applied for equipment design and quality control [7]. But, most of these characterization techniques are flow indicators and have limitations such as reproducibility, predictability, sensitivity and are often time consuming and user dependent. In addition, the available test methods do not represent the conditions that powders undergo during manufacturing and end-use application. Furthermore, flow is a complex issue which could not be explained by a single numerical value but, requires detailed evaluation of properties that influence flow. To overcome this challenge, a range of characterization methods is required to ensure a complete understanding of the flow behavior of any given powder material.

Some factors that affect flowability are moisture content, humidity, temperature, pressure, fat content, particle size, and shape. Moisture plays a key role in flow properties of a granular material. As the moisture content of a powder increases, the adhesion and cohesion [8] tend to increase. Many studies have examined the effect of moisture content on physical and flow properties of granular solids and powders [8–13] and significant effect of moisture on various properties were reported.

Recently, the advancement in measurement technologies has resulted in instruments that could measure the dynamic flow properties of powders. These instruments

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allow measurement of powder response to various environments, simulating the processing conditions more practically. Some of these properties and measurement techniques could be found in Freeman et al. [14], and Leturia et al. [15]. During dynamic flow property measurements, in order to ensure repeatable and comparable data, a conditioning procedure allows the generation of a stable consolidation state that can be reproduced consistently. In addition, the fully automated testing procedures minimize operator error.

With the increased use of coconut flours in the manufacture of food and feed products, it is important to have an understanding on their flow characteristics. But, there is lack of published data on the flowability of coconut flours. For proper use of coconut based flours by the bakery, confectionery, extrusion, and livestock feed industry, the dynamic flow behaviour of coconut flours will be helpful. Therefore, the objective of this study was to examine the effect of moisture content on the dynamic flow characteristics of coconut based flours of MRF and CF in the moisture content range of 4–8 % (wet basis, w.b.).

2 Materials and methods

2.1 Samples

Coconut flours were prepared from eleven months old matured West Coast Tall coconut variety. MRF was prepared by milling the dried coconut milk residue obtained during the extraction of coconut milk. CF was prepared by milling the dried virgin coconut oil cake obtained during the extraction of virgin coconut oil. A 50 kg/h capacity pulverizer (M/s Pilotsmith, Thrissur, Kerala, India) was used to mill MRF and CF. A feed rate of 40 kg/h was maintained during milling. Flours that passed through a 0.63 mm mesh screen fixed in the pulverizer was collected and used for flow property measurement. The proximate composition, total dietary fiber, free fatty acid, and peroxide value of the samples were determined using the standard methods [16] from an external lab. Particle size distribution was measured using the ASABE S319.4 method [17] 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.

The initial moisture content of these flours was about 3 % (w.b.). In general, coconut flour are stored and transported at a low moisture content and tend to agglomerate above 8 % w.b. moisture content. Hence, experiments were conducted within the moisture content range of 4–8 % (w.b.). Higher moisture content samples were prepared by adding calculated amount of water based on their dry matter content [18]. Distilled deionized water was sprayed uniformly onto the flour and thoroughly mixed in a flour conditioning bin for 1 h. Water was added in increments to avoid agglomeration of the flour. Drying to desired moisture level was carried out on the lab bench in ambient conditions (22–23 °C) by spreading the samples in thin layer without any additional hear or airflow. After drying, for moisture equilibration, the conditioned samples were then stored at 4 °C for 72 h before the experiments. After conditioning, the final three levels of moisture content of samples were 4.53 ± 0.10, 6.23 ± 0.06 and 8.18 ± 0.12 % w.b.; 3.85 ± 0.03, 6.01 ± 0.04 and 7.98 ± 0.36 % w.b. for MRF and CF, respectively. The conditioned samples were stored at 4 °C till actual testing.

2.2 Dynamic flow property measurement

The FT4 powder rheometer (FT4, Freeman Technologies, Gloucestershire, UK) was used to measure the dynamic flow, bulk and shear properties of coconut flours. The dynamic flow properties were assessed under packed bed, free surface and aerated condition. The tests under packed bed conditions are used to predict the flow (or no flow) of bulk solids from a storage vessel with a given outlet size. The tests under free surface conditions are representative of the filling of bulk solids into a small packing container. The aerated conditioned tests are measures of the permeability or fluidization behavior of bulk solids. Detailed descriptions of dynamic flow property measurement procedure can be found in Bian et al. [19, 20] and Lindberg et al. [21].

The dynamic flow measurement methodology used definite volume of flour samples that were tested in a 50-mm diameter borosilicate glass cylinder. The flour was made to flow by moving a 48-mm-diameter twisted blade, rotationally and axially, so that the powder moved along a helical path through the sample. A pre-conditioning process establishes a consistent and reproducible packing density of powders in the glass cylinder. The sample was first prepared by conditioning and splitting using the standard 48 mm blade and 50 mm × 160 ml split vessel assembly. The conditioning cycle consisted of a downward and upward movement of blade at 5° helix angle and 60 mm/s blade tip speed. The test cycle that followed moved the blade along a downward helical path (5° helix angle at a blade tip speed of 100 mm/s), but in the opposite direction to impose compaction, thereby forcing the flour to flow around the blade. The axial and rotational forces acting on the blade during the cycle were measured continuously and used to derive the work done, or energy consumed, in displacing the flour. The flow properties, described below, were evaluated during the displacement of powders in a controlled manner.

2.2.1 Flow properties at free surface conditions

Basic flowability energy (BFE): The energy required to establish a specific flow pattern for a precise volume of particulate solid materials is called the BFE. BFE indicates the effect of moisture, milling, agglomeration, etc on flow of particulate materials. BFE is calculated from the work done in moving the powder rheometer blade at 100 mm/s tip speed.

Stability index (SI): The stability index assesses the ability of powder to agglomerate, segregate or break during flow. The stability is measured through a 7-cycle test and stable samples would result in similar measurements during the repeated measurements. All tests cycles were conducted at 100 mm/s blade tip speed.

Flow rate index (FRI): The flow rate index is the ratio between flow energy at 10 mm/s blade tip speed and flow energy at 100 mm/s blade tip speed. Flow rate depends on the intrinsic properties of powders such as cohesion, particle size, etc and bulk powders are sensitive to changes in flow rate. Characterizing flow rate of flour will help understand the process of conveying of powders during handling and processing [20].

Specific energy (SE): The specific energy is a measure of how flour will flow in an unconfined or low stress environment. It is calculated from the energy required to establish a particular flow pattern in a conditioned, precise volume of flour. This flow pattern is an upward clockwise motion of the blade, generating gentle lifting and low stress flow of the flour. The SE is calculated from the work done in moving the blade through the flour from the bottom of the vessel to the top, i. e. during the upward traverse. It is then normalised against mass of the samples.

Consolidation energy (CE) and Consolidation index (CI): Samples were consolidated by tapping 50 times prior to measuring CE and CI. The standard test at 100 mm/s blade tip speed was then run to determine the increase in energy requirement to make the powder flow. The ratio of the increased energy (CE) to the BFE was then reported as the CI. Particulate materials are subjected to uncontrolled vibration due to equipment vibration during processing or during transportation. An understanding of CE and CI will help the process engineer to predict potential challenges due to vibration and consolidation of powders during processing and flow.

2.2.2 Compressibility

Compressibility is a measure of density changes as a function of applied normal stress. For flours, this bulk property is influenced by factors such as particle size distribution, cohesion, particle stiffness, particle shape, and surface texture. Compressibility relates to many process environments such as storage in hoppers or super sacks or behaviour during roller compaction and extrusion. A vented piston was used to compress the powder samples under increasing normal stress from 0.5 kPa to 15 kPa (0.5, 1, 2, 4, 6, 8, 10, 12, and 15 kPa). Each normal stress is applied for 60 sec to allow the flour to reach equilibrium at the target stress. The distance travelled by the piston was measured at each applied normal stress and the compressibility was calculated from the percentage change in volume.

2.2.3 Aeration

The bulk properties of granular materials are affected by air to some extent because of the presence of air in inter-granular space. The amount of air present in the bulk or the porosity influences the inter-particle interaction and their ability to aerate. Easily aeratable powders have better bulk flow properties because the powders start behaving as fluids and a small amount of energy is sufficient to initiate flow. In this study, samples were aerated by supplying air to the base of the test vessel i. e. by using aerated base assembly. The standard test was repeated at airflow rates of 0, 2 4, 6, 8, and 10 mm/s between the conditioning cycles to determine how the flow energy varied for various levels of aeration, at all experimental moisture levels. The blade tip speed was kept constant at 100 mm/s. Aeration ratio (AR) is then calculated from the ratio of BFE at 0 mm/s and 10 mm/s.

2.2.4 Shear test

Shear properties are important for understanding how easily a previously at rest, consolidated flour will begin to flow. In every process and storage environment, flours will be subjected to consolidation stresses causing changes in density and mechanical inter particulate forces. Measuring the shear properties will provide important information as to whether the flour will flow through the process or whether bridging, blockages and stoppages are likely. The rotational shear cell module of the powder rheometer was used for shear test which consists of a vessel with serrated base containing the flour sample and a shear head to induce both vertical and rotational stresses. The normal stress was maintained constant throughout the shear analysis. The maximum shear stress is the point of incipient failure or the yield point. A series of yield points for a range of reducing normal stresses is measured. Each shear analysis steps contain pre-shear, hold and shear sections. In this study, shear stress was determined at normal stresses of 3, 6, 9, and 15 kPa. Yield locus was drawn in the plot of maximum shear stress and normal stress. From the yield locus, the cohesion, internal friction angle, unconfined yield strength, major consolidation stress, minor consolidation stress, flow function, flow index, and shear stress were calculated using Mohr's circle analysis [14].

2.2.5 Wall friction

The wall friction developed between the flour and the hopper wall surface is very important for flour flowability as it is the dominant factor in determining the flow pattern that exists during discharge, provided that no arching occurs. Flour properties and storage and handling conditions may influence the wall friction characteristics of flours and thus influence the flow pattern during silo discharge. The rotational wall friction module of a 50 mm × 85 ml split vessel with serrated base assembly and a wall friction head with 0.28 μm surface roughness were used to induce both normal and shear stresses for wall friction angle measurement [22]. The wall friction head was made to move downwards in the test material until the establishment of the required normal stress (3, 6, 9 and 15 kPa). A shear stress (3, 6, 9 and 15 kPa) was established by slow rotation of the wall friction head at 18°/min for 5°. The wall yield locus was obtained by measuring the horizontal shear stress required to make the flour fail at the normal stresses. The angle of wall friction (φ_w) was the angle formed with the horizontal by a line drawn from the origin to a point on the wall yield locus with a normal stress.

2.3 Statistical analysis

Each dynamic flow property was measured in triplicate and the mean values with standard deviation at 5 % significance levels are reported in this paper. Statistical analyses (analysis of variance, standard deviation, multiple comparison procedure etc.) were performed using the statistical software package of Microsoft Excel 2007 (Microsoft Corporation, Redmond, WA, USA).

3 Results and discussion

3.1 Chemical composition

The geometric mean diameter of CF (594.56 ± 5.64 μm) was significantly higher than the MRF (524.77 ± 10.68 μm). The reduction in flowability might be due to reduction in particle size which leads to increase in surface area and cohesion [23]. The particle sizes were closer to the 0.63 mm screen used during the milling process, but the difference in geometric mean diameter could be from different breakage pattern of the components. Protein and ash content of CF was significantly higher than the MRF (Table 1).

Table 1: Chemical composition of coconut flours.

Chemical composition	MRF	CF	*F-value*	*P-value*
	Mean ± SD	Mean ± SD		
Crude protein, % N × 6.30	5.3 ± 0.1^{a}	20.1 ± 0.1^{b}	$60{,}771.2^{**}$	1.6E-09
Initial moisture content, %w.b.	2.9 ± 0.2^{a}	3.1 ± 0.1^{a}	4.8^{NS}	9.0E-02
Crude fat, %	49.2 ± 0.7^{a}	35.6 ± 0.2^{b}	$1{,}218.5^{**}$	4.0E-06
Crude fiber, %	25.5 ± 0.7^{a}	3.8 ± 1.7^{b}	409.6^{**}	3.5E-05
Ash, %	0.9 ± 0.0^{a}	6.1 ± 0.1^{b}	$11{,}131.2^{**}$	4.8E-08
Total dietary fiber, %	46.5 ± 0.4^{a}	12.8 ± 0.3^{b}	$15{,}507.7^{**}$	2.5E-08
Free fatty acids, %	1.2 ± 0.0^{a}	1.79 ± 0.1^{b}	278.4^{**}	7.6E-05
Peroxide value, mEq/kg	0.3 ± 0.0^{a}	0.6 ± 0.1^{b}	101.1^{**}	5.5E-04

Note: SD – Standard deviation at α = 0.05 level; values with similar superscripts in the same rows for a given property are not significantly different and values followed by different superscripts are significant at α = 0.05 level.
^{NS} – Not significant; ** – Significant at α = 0.01 level.

However, fat and fiber contents were higher in MRF. Higher presence of fat could be a major factor leading to higher cohesion in coconut flours. Fitzpatrick et al. [23] also observed a decrease in flow index value with increase in fat content.

3.2 Flow properties of flour at free surface and consolidated condition

The BFE data of MRF and CF at different moisture levels indicated that they were relatively stable at lower moisture level and the energy consumption was either in increasing or decreasing trend in progression of the tests at higher moisture levels (Figure 1). The BFE of CF increased significantly with moisture content (Table 2) and was higher than that for MRF. The potential agglomeration of CF at higher moisture level might have increased the BFE values [15]. This reflects its higher packing density and the greater forces required to cause the powder to flow under compaction [21]. The smaller particle size of MRF might have resulted in lower BFE compared to CF. The average values indicate that the flow properties of CF would be better than the flow properties of MRF. Bian et al. [20] measured BFE of hard and soft wheat flours as 680.70 mJ and 713.19 mJ respectively at 11.4 % moisture content (wb). The stability index varied from 0.96 to 1.02 for MRF and 0.942 to 1.157 for CF (Table 2), whereas hard and soft wheat flour recorded stability indices as 1.09 and 1.10 respectively [20]. Because the stability index values of both the flours are closer to 1, the flours do not segregate and will not be affected by being made to flow [22]. Flow rate index of MRF was higher than the CF. The flow rate index values close to 1 indicate that the powders are not sensitive to flow [20] and it was found as 1.05 and 1.86 for spray dried and finely milled lactose powders respectively [22]. The specific energy increased linearly with moisture content and it varied from 5.56 to 5.99 mJ/g and 3.76 to 6.00 mJ/g for MRF and CF, respectively (Table 2); and 4.80 mJ/g and 9.60 mJ/g for spray dried and finely milled lactose powder respectively [22]. The values indicate that MRF are cohesive within the tested moisture content range. This could potentially affect the flow of this powder material from bins or hopper bottom storage vessels [15]. CF was found to be cohesive at 7.98 % moisture content.

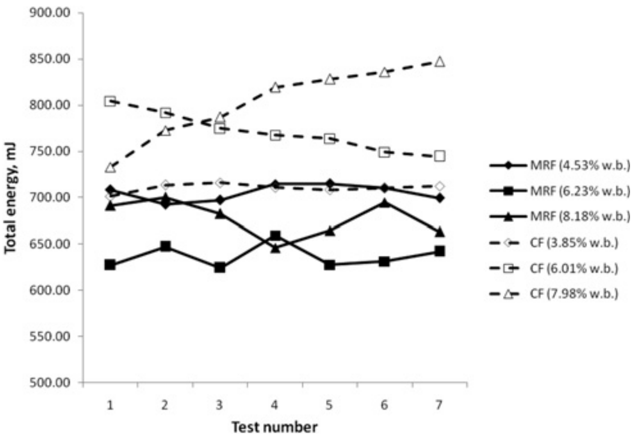

Figure 1: Energy consumption during dynamic flow of coconut flours.

The consolidated energy of CF increased with moisture while for MRF, the consolidated energy decreased with increase in moisture content (Table 2). Similar to BFE, consolidated energy of CF was higher than that of MRF. There was significant difference (at 5 % level) in consolidated energy of MRF due to moisture content but

Table 2: Effect of moisture on free surface and consolidation based flow properties of coconut flours.

Property	MRF				CF			
	Moisture content, % w.b.			*F-value*	Moisture content, % w.b.			*F-value*
	4.53	**6.23**	**8.18**		**3.85**	**6.01**	**7.98**	
Basic flowability energy, mJ	699.3 ± 25.8^{a}	642.1 ± 12.4^{b}	663.4 ± 12.8^{c}	7.7^{*}	712.3 ± 15.9^{a}	744.5 ± 10.7^{b}	847.3 ± 9.2^{c}	99.4^{**}
Stability index	1.0 ± 0.1^{a}	1.0 ± 0.0^{a}	1.0 ± 0.0^{a}	2.1^{NS}	1.0 ± 0.0^{b}	0.9 ± 0.0^{a}	1.2 ± 0.1^{c}	43.6^{**}
Flow rate index	1.1 ± 0.1^{a}	1.1 ± 0.1^{a}	1.2 ± 0.0^{a}	0.5^{NS}	1.1 ± 0.0^{a}	1.1 ± 0.0^{a}	1.0 ± 0.0^{b}	10.8^{*}
Specific energy, mJ/g	5.6 ± 0.1^{a}	6.0 ± 0.1^{b}	5.9 ± 0.1^{b}	24.4^{**}	3.8 ± 0.1^{a}	4.4 ± 0.2^{b}	6.0 ± 0.2^{c}	147.1^{**}
Consolidated energy, mJ	863.8 ± 32.1^{a}	806.2 ± 16.4^{b}	784.5 ± 12.8^{c}	6.1^{*}	959.1 ± 5.8^{a}	$1{,}080.1 \pm 21.0^{b}$	$1{,}152.4 \pm 19.8^{c}$	99.4^{**}
Consolidation index	1.2 ± 0.1^{a}	1.2 ± 0.1^{a}	1.2 ± 0.0^{a}	0.1^{NS}	1.4 ± 0.0^{a}	1.5 ± 0.0^{b}	1.4 ± 0.0^{a}	13.3^{**}

Note: ± Standard deviation at $\alpha = 0.05$ level; values with similar superscripts in the same rows for a given property are not significantly different andvalues followed by different superscripts are significant at $\alpha = 0.05$ level; ^{NS} – Not significant; * – Significant at $\alpha = 0.05$ level; ** – Significant at $\alpha = 0.01$ level.

for CF, it differed significantly at 1 % level (Table 2). The tendency to agglomerate at elevated moisture content might have resulted in a decreasing trend of consolidation energy for MRF. There was no significant difference due to the effect of moisture content on consolidation index of the coconut flours.

3.3 Flow properties at consolidated condition

The percent compressibility of both flours, at all applied normal stress, increased significantly with increase in moisture content (Figure 2). The percent compressibility of MRF varied from 8.38 to 32.7 % whereas for CF, it varied from 2.61 to 17.45 %. The higher cohesion between the MRF particles resulted in greater compressibility percentage. The greater the compressibility of a bulk solid, the less flowable it is. In high moisture powders, strong inter particles forces cause the open structure to collapse under pressure, thus increasing the compressibility [24]. The statistical analysis indicated the influence of moisture and applied normal stress on compressibility of coconut flours. Moreyra and Peleg [25] also reported on the higher compressibility of moist powders as compared with dry or less cohesive powder.

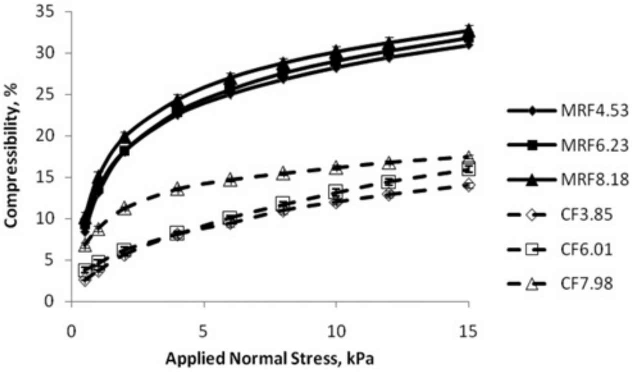

Figure 2: Effect of moisture content and applied normal stress on compressibility of coconut flours.

3.4 Flow properties at aerated condition

Aeration reduced the total energy required to make the powder flow. Aeration helps the flour particle to break the interparticulate cohesive forces that prevents flow. While moisture content had a proportional significant effect on the energy required (Table 3). The cohesive nature of the flours at higher moisture resulted in an increased energy required to make the powder flow. The results indicate that even flow of these flours from hoppers and bins could be achieved with air assisted discharge and will avoid formation of interlocking arches. There was no significant difference between aeration ratios of MRF at all tested moisture levels but, moisture content had a significant influence on the aeration ratio of CF. The higher the aeration ratio (AR) and the lower the aerated energy (AE), the less cohesive is the powder [22]. Based on this interpretation, CF at 3.85 % moisture content had greater AR (1.13) and lower AE (1,098.18 mJ) and hence less cohesive. This is the most positive indicator of good flowability, particularly when the powder is unconfined and able to aerate. The reason for this high AR value is likely to be that the interparticulate bonding is less at lower moisture so that the powder is able to fluidize, in which state it requires very little energy to promote flow [21]. Freeman [22] observed aerated energy of spray dried and coarsely milled lactose

Table 3: Effect of moisture content and air velocity on mean flow energy and aeration ratio of coconut flours.

Property	Air velocity, mm/s	MRF				CF			
		Moisture content, % w.b.			*F-value*	Moisture content, % w.b.			*F-value*
		4.53	6.23	8.18		3.85	6.01	7.98	
Flow energy, mJ	0.0	1,069.8 ± 27.8^{a}	1,201.5 ± 26.9^{b}	1,224.6 ± 43.6^{b}	18.5**	1,241.4 ± 15.4^{a}	1,289.5 ± 5.5^{b}	1,360.3 ± 13.6^{c}	71.6**
	2.0	1,072.0 ± 15.1^{a}	1,197.1 ± 12.9^{b}	1,239.9 ± 70.8^{b}	12.7**	1,225.2 ± 5.7^{a}	1,243.9 ± 25.4^{a}	1,343.7 ± 21.0^{b}	32.7**
	4.0	1,080.9 ± 19.7^{a}	1,183.2 ± 9.8^{ab}	1,236.2 ± 68.0^{b}	11.0**	1,184.5 ± 15.0^{a}	1,230.8 ± 29.9^{a}	1,335.0 ± 10.0^{b}	43.9**
	6.0	1,065.8 ± 8.9^{a}	1,184.2 ± 27.2^{b}	1,220.6 ± 18.0^{b}	51.6**	1,137.2 ± 15.3^{a}	1,194.0 ± 30.6^{a}	1,326.6 ± 11.9^{b}	64.8**
	8.0	1,040.6 ± 25.9^{a}	1,151.6 ± 34.7^{b}	1,209.9 ± 58.9^{b}	12.4**	1,120.5 ± 18.1^{a}	1,170.1 ± 28.1^{a}	1,320.1 ± 25.4^{b}	54.0**
	10.0	1,023.7 ± 33.5^{a}	1,126.6 ± 30.4^{b}	1,198.6 ± 67.9^{b}	10.4**	1,098.2 ± 13.4^{a}	1,160.1 ± 16.9^{a}	1,318.8 ± 37.0^{b}	64.7**
Aeration ratio		1.1 ± 0.0^{a}	1.1 ± 0.1^{a}	1.0 ± 0.1^{a}	0.6^{NS}	1.1 ± 0.0^{a}	1.1 ± 0.0^{a}	1.0 ± 0.0^{b}	17.7**

Note: ± Standard deviation at $\alpha = 0.05$ level; values in the same rows followed by different superscripts are significant ($p < 0.05$); ^{NS} – Not significant; * – Significant ($p < 0.05$); ** – Significant ($p < 0.01$).

powders at 14 mm/s air velocity as 156 mJ and 181 mJ respectively.

3.5 Shear flow properties of coconut flours

The cohesion increased significantly with applied normal stress and major consolidating stress for both the coconut flours (Figure 3). At all applied normal stress and moisture levels, the cohesion of MRF was greater than that of CF. Similar to the dynamic flow property results, the shear tests also indicated that moisture content had a significant effect on the cohesion of CF. Powders with high cohesion values tend to agglomerate at higher moisture contents [24]. However above certain moisture content (for e. g. 6.23 % for MRF at 3 and 6 kPa consolidation pressure), moisture may act as a lubricant and improve flow [23]. The trend of BFE and SE (Table 2) was similar to cohesion in case of CF. Cohesion of coconut flours was lower than that of sugar [26], potato starch and soy flour [24], but higher than that of chickpea flour [27] and wheat flour [28].

The unconfined yield strength (UYS) of both the coconut flours at three moisture contents are presented in Figure 4. Statistical analysis ($p < 0.05$) indicated that the moisture content did not significantly affect the unconfined yield strength values (σ_c) at different consolidating stresses (σ_1) for MRF. But for CF, moisture had a significant effect on the UYS. The flow index can also be applied to the food powders tested, as the slopes of the flow functions increase in the anticlockwise direction from the region of easy flow to difficult flow. This was confirmed from the values of the flow index (obtained from the inverse of the slope of the linear fit of the σ_c versus σ_1 plot; Figure 4), which were respectively 3.23, 2.95 and 3.32 for MRF at 4.53, 6.23, and 8.18 % moisture content; 4.40, 2.85, and 2.65 for CF at 3.85, 6.01 and 7.98 % moisture content respectively. We observed the increase in BFE and SE (Table 2) lead to decrease in flow index in case of CF. Based on Jenike's classification [29], MRF and CF can be classified as cohesive materials except for CF at 3.85 % moisture content which can be classified as an easy flowing material. Flow aids will therefore be required during the discharge of MRF and CF from storage bins and hoppers. Fitzpatrick et al. [23] also observed a decrease in flow index of skim milk powder, whole milk powder and high fat milk powder with increase in moisture.

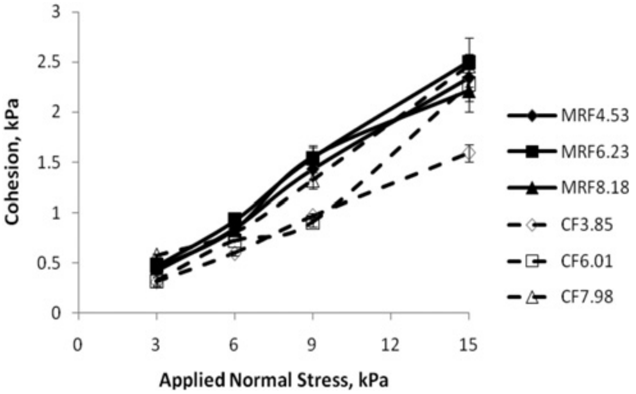

Figure 3: Effect of moisture content and applied normal stress on cohesion of coconut flours.

The angle of internal friction (AIF) of both the samples was not significantly affected ($p < 0.05$) by moisture content or by consolidating pressure ($p < 0.05$) except for CF at 15 kPa pressure (Table 4). AIF values ranged from 38.93° to 41.90° for MRF and 37.07° to 41.46° for CF. These values are less than the angles of internal friction that were reported by Fitzpatrick et al. [30] for 13 food powders (42° to 65°). The critical values of angle of internal friction for gravity discharge of bulk materials from bin is 30° at 2 kPa [31]. The measured values for coconut flours are greater than this reported critical value. Hence, gravity discharge cannot be used to unload these samples from storage bins and will require discharge aids to make the bulk of coconut flour to flow.

Wall friction characteristic is very important as this has a major role in determining the discharge pattern (mass or funnel flow) from the storage bin. The wall friction angle increased significantly with moisture and

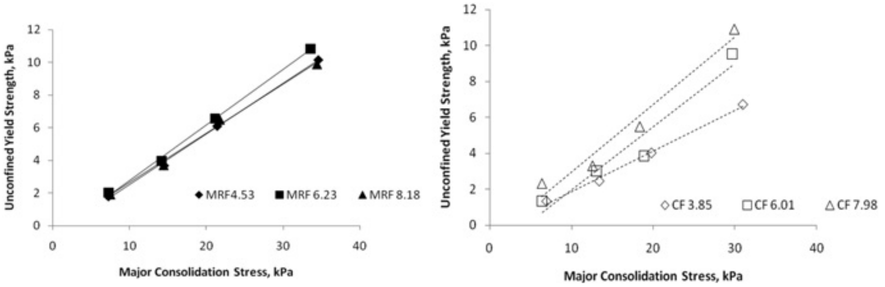

Figure 4: Effect of moisture content and major consolidation stress on unconfined yield strength.

Table 4: Effect of moisture content and applied normal stress on friction coefficients.

Property	Applied normal stress, kPa	MRF				CF			
		Moisture content, % w.b.			*F-value*	Moisture content, % w.b.			*F-value*
		4.53	6.23	8.18		3.85	6.01	7.98	
Angle of internal friction, °	3.0	40.4 ± 0.4^{a}	40.2 ± 0.9^{a}	39.9 ± 0.8^{a}	0.5^{NS}	40.3 ± 0.9^{a}	38.8 ± 1.1^{b}	37.1 ± 1.3^{b}	6.4^{*}
	6.0	41.0 ± 1.2^{a}	40.4 ± 0.7^{a}	41.5 ± 1.3^{a}	0.8^{NS}	38.9 ± 0.4^{a}	38.3 ± 1.9^{a}	38.4 ± 0.6^{a}	0.3^{NS}
	9.0	39.9 ± 1.1^{a}	39.6 ± 1.1^{a}	38.9 ± 0.6^{a}	0.8^{NS}	38.7 ± 0.1^{a}	39.6 ± 1.0^{a}	38.6 ± 0.8^{a}	1.6^{NS}
	15.0	40.6 ± 1.0^{a}	40.4 ± 0.9^{a}	41.9 ± 1.7^{a}	1.3^{NS}	38.7 ± 0.7^{a}	39.1 ± 0.7^{a}	41.5 ± 0.3^{b}	18.9^{**}
Wall friction angle, °	3.0	14.8 ± 0.3^{a}	16.5 ± 0.6^{b}	18.7 ± 0.5^{c}	50.8^{**}	14.3 ± 1.1^{a}	18.2 ± 0.4^{b}	23.0 ± 0.9^{c}	77.9^{**}
	6.0	13.7 ± 0.6^{a}	15.8 ± 0.1^{b}	17.8 ± 1.0^{c}	28.4^{**}	12.4 ± 0.4^{a}	13.7 ± 0.4^{a}	19.7 ± 1.3^{b}	71.4^{**}
	9.0	13.1 ± 0.2^{a}	14.5 ± 0.2^{b}	15.2 ± 0.3^{c}	73.0^{**}	12.0 ± 0.4^{a}	13.5 ± 1.3^{a}	14.4 ± 0.8^{b}	556.1^{**}
	15.0	12.7 ± 0.1^{a}	12.4 ± 0.1^{a}	13.4 ± 0.6^{b}	5.7^{*}	10.5 ± 0.2^{a}	12.7 ± 0.6^{b}	13.6 ± 0.9^{c}	69.5^{**}

Note: ± Standard deviation at $\alpha = 0.05$ level; values in the same rows followed by same letter (a) are not significant ($p < 0.05$); ^{NS} – Not significant; * – Significant ($p < 0.05$); ** – Significant ($p < 0.01$).

decreased with applied normal stress (Table 4). The values ranged from 12.41° to 18.66° for MRF and 10.50° to 22.99° for CF. Iqbal and Fitzpatrick [32] reported that surface stickiness from the presence of moisture increases the adhesion between particles and the wall surface. Cohesive material generally has higher wall friction angle and adheres more strongly to the wall material. Due to this higher wall friction angle, a steeper hopper angle is required to obtain mass flow for high moisture coconut flours. If the angle of hopper is less than the minimum required for mass flow, there is a likelihood that the hopper will discharge in funnel flow which may result in rat holing and bridging. These results demonstrate that moisture content can have significant influence on the wall friction characteristics of powders, which in turn influence their discharge pattern from hoppers and silos [33].

4 Conclusions

The dynamic flow properties of two coconut coproducts at different moisture content levels under free surface, consolidated, compressed, aerated, and shear conditions were measured using a powder rheometer. The moisture content did not affect the flow rate index of MRF and the flow rate index of CF decreased significantly with moisture content. Based on specific energy values, the CF could be categorized as less cohesive at 3.85 % and 6.01 % moisture content. Meanwhile MRF behaved as a highly cohesive powder material at all experimental moisture levels. Our results showed that MRF at 8.18 % moisture content was the most compressible and CF at 3.85 % moisture content was the least compressible at all the combinations of consolidating pressure within the tested moisture content levels. The cohesion of MRF was greater than that of CF and increased significantly with applied normal stress and major consolidating stress for both the flours. Flow aids will be required during the discharge of cohesive MRF and CF from storage bins and hoppers based on flow index values. Gravity discharge cannot be used to unload the tested coconut flours from storage bins in view of higher than the critical value (30°) of angle of internal friction of both the flours. The wall friction angle for both the flours increased significantly with moisture and decreased with applied normal stress and hence steeper hopper angle is required to obtain mass flow for the high moisture flour. The results of this study will be helpful in designing handling, flow and processing systems for coconut powders.

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