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Flow and strength properties of cassava and yam starch–glycerol composites essential in the design of handling equipment for granular solids

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ABSTRACT

A research was conducted to determine the flow and strength properties of cassava and yam starch–glycerol composites for their application in the design of hopper or any other storage bin, with a consistent flow during the handling of the granular solids, in the food industry. The flow and strength properties of the bulk materials which include the consolidation, shear and unconfined yield stresses were determined at different bulk densities and glycerol concentrations in the range of 1.5–3.0 g/cm^3 and 15–25 ml glycerol per 100 g starch using a uniaxial compression test. The flowability of the bulk solids were classified using Jenike's flow specifications. The angles of internal and wall frictions of the bulk solids were determined from their yield loci. The hopper half angles were determined from the conical hopper design chart; and the friction factors, which account for the vibration in the arch thickness and the geometric configuration of the composites, were computed empirically. The results show that the compressive strength of the cassava and yam starch–glycerol composites increased significantly with an increase in bulk density and a decrease in the glycerol concentration ($p < 0.05$). The cohesiveness of the composites increase with increasing glycerol concentration, up to 25 ml per 100 g starch, because of their increasing flow function ($1 < ff < 2$). The hopper half angle, friction factor and angles of internal and wall frictions of the cassava starch–glycerol composite at 3.0 g/cm^3 were 18.0°, 2.48, 43.0° and 26.0°, respectively. The higher angle of wall friction at 3 g/cm^3 implies that a steeper hopper wall is required for a consistent flow of the granular solids through a hopper.

1. Introduction

The food industry is one of the largest commercial enterprises contributing immensely to the gross domestic product of many countries in the world today. Numerous raw materials in this industry are in powdered or granulate form, and their optimum handling and processing rely heavily on the deep knowledge of their particle technologies. The measurement of the properties of the granular solids is important because these properties inherently affect their behavior during storage, handling and processing (Fitzpatrick et al., 2004). The handling and processing of the granular materials however, are usually aided by the use of a hopper, silo or conveyor. Many different shapes of the hopper and silo are routinely used in the food industry but, in each case, the reliability of the equipment for steady powder discharge depends on the design parameters considered. Thus, selecting an appropriate outlet size and half angle of the hopper or silo will help achieve this.

The flow regimes from a hopper or silo can either be mass or funnel in practice. The preferred option for the majority of applications is the mass flow where all of the powder is in motion as the material is withdrawn at the exit, producing a 'first in, first out' regime which tends to be relatively consistent as the full capacity of the bin is used. With funnel flow, on the other hand, there is an active channel down the center of the vessel but the powder stagnates along the hopper or bin wall. A steeper hopper wall with a smaller hopper half angle encourages mass as oppose to funnel flow (Knowlton et al., 1994; Peleg, 1978). Funnel flow produces 'last in, first out' powder delivery and a greater likelihood of operational problems such as rat-holing, segregation and flooding. Rat-holing is where a central void develops above the discharge outlet in place of the active flow channel. The collapse of the

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rat-holes can cause a significant mechanical damage and an excessive aeration of the powder. Generally, aeration in the active flow channel encourages flooding and segregation both of which are undesirable. When this occurs, the powder becomes fluid-like and flows uncontrolled in the bin; and only then will the particles become separated on the basis of size. While these operational disadvantages discourage the use of the funnel flow, it can be the preferred choice when the building height is limited for instance. The funnel flow designs of a hopper or silo can be short and wide with shallow side angles; while the mass flow units of the same capacity are often made taller with a smaller cross-sectional area (Johanson, 2002; Purutyan et al., 1998).

The flows of granular materials through a given hopper often depend on their flow properties. But, flowability is not an inherent material property; it is rather the result of the combination of material physical properties that affect flow and the equipment used for its handling and processing. However, equal consideration must be given to both the material characteristics and the equipment. A given material may flow well in one hopper but poorly in another. Likewise a given hopper may handle one material well but cause another to hang up. Therefore, the flowability of a granular material can be defined as its ability to flow in a desired manner in a specific piece of equipment (Bumiller et al., 2012). The specific bulk characteristics and properties of the granular materials that affect flow, which can in principle be measured, are known as the flow properties. These properties refer to the behavior of the bulk material, and arise from the collective forces acting on the individual particles, such as the van der Waal, electrostatic, surface tension, interlocking, and friction (Bumiller et al., 2012). These collective forces define how the granular solids will behave in the hopper or silo when consolidated by the weight of the material in the bin. Potentially, a stable arch can form across the hopper outlet when the consolidation stress generated in an arch at the outlet and the weight of the bulk solid discharging balances each other, as is shown in Fig. 1. If the arch formed is strong enough to support the rest of the material in the vessel then discharge ceases. Also, for any given combination of the granular solids and the material of construction, the magnitudes of the hopper half angle and the outlet size determine whether a stable arch will form. The design methodology, which is based on the detailed analysis of flow and no flow conditions, as carried out by Jenike (1964) remains the standard today.

The knowledge of the parameters of internal friction and flow properties of the granular solids is required in the design of reliable processes and efficient equipment for the products (Knowlton et al., 1994). Moreover, an understanding of the fundamental mechanism of the compression behavior of the granular solids is paramount in the design of energy efficient compaction equipment in the food industry. This is essential to mitigate the cost of production and enhance the quality of the product (Mani et al., 2004). The flow characteristics of the granular solids have recently gained special importance as measures of the quality of final product on-line, as well as during the later handling and on-shelf storage (Molenda and Stasiak, 2002). However, the flowability of the granular solids depends on the relationship between the adhesive forces to the other forces acting on them. The influence of the adhesive forces on the flow behavior increases with a decrease in the particle size. Thus, as a rule, a granular solid flows poorly with a decrease in the particle size. Fine-grained solids with a moderate or poor flow behavior due to adhesive forces are called cohesive granular solids. If the particles are pressed against each other by an external force, the compressive force acting between the particles increases. This causes large stresses to prevail locally at the particles' contact points, leading to an increase in the plastic deformation at the contact area as the particles approach each other. Thus, the compressive force acting on a granular solid element from outside can increase the adhesive forces. The dependence of the adhesive forces between the particles on the external forces is a characteristic of most cohesive granular solids. Therefore, an evaluation of the flow behavior of the granular solids must always consider the forces or stresses previously acting on them, the consolidation stress leading to certain adhesive forces exerted on them, and hence the strengths of the granular solids (Schulze, 2011).

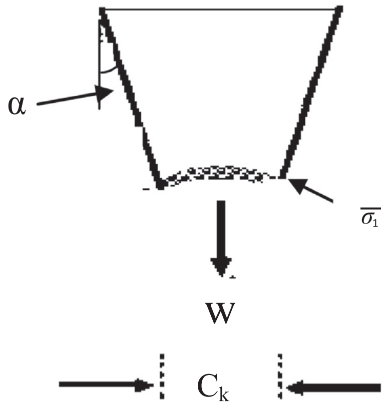

Fig. 1. Forces acting within the hopper to prevent stable arch formation ($\sqrt{\sigma_1}$ = consolidated stress generated in an arch at the outlet (kPa), W = weight of the discharged granular solid (N), α = hopper half angle (degree) and C_k = hopper outlet size (m)) (Schulze, 2011).

A number of methods and testers exist in the literature for determining the strength and flow properties of the bulk solids. Schwedes (2002) reported that choosing the right method for a specific application requires the knowledge and some experience of handling the bulk materials. The flow properties of the bulk materials, either in their powdered or granulate form, are frequently determined by performing a shear test following a slightly modified procedure proposed by Jenike (1964) (Fitzpatrick et al., 2004). The use of a more direct method, such as the uniaxial compression test, in the measurement of the flow properties of the granular materials has been reported; although not so for the cassava or yam starch granules (Schwedes, 2002). Unfortunately, the design of specific equipment for the handling of the cassava and yam starch granules is an arduous task because of the limited available information on the flow and strength properties of the products in the literature. Thus, there is the need to investigate these properties in order to design the handling equipment for the products. The objective of this research is to determine the flow and strength properties of the cassava and yam starch–glycerol composites such as the angles of internal and wall frictions, friction factor, consolidation, shear and the unconfined yield stresses for their application in the design of the hopper, silo, conveyor or any other storage bin, for a consistent flow during the handling and processing of the granular solids, in the food industry.

2. Materials and methods

2.1. Sample preparation

The starches used in this experiment were prepared from a freshly harvested cassava roots and yam tubers. Two hundred and fifty kilograms each of the produce were pealed and soaked in two separate clean bowls containing water for 24 h after which they are ground into pastes. The ground pastes were then sieved using a muslin cloth and the resulting filtrates were left undisturbed for 24 h to allow the starches to settle at the bottom of the bowls. The prepared starch of the cassava and yam were dried under the sun for one week until a moisture content of 2% (wb) was achieved.

The starch composites were prepared by adding a 15, 20 and 25 ml analytical grade glycerol, obtained from Science Equipment and Development Institute (SEDI), Minna, Niger State, Nigeria, in 100 g of the dried cassava and yam starches. The mixtures were then stirred thoroughly with the aid of a spatula and kept for 2 h for hydration. The bulk density of the hydrated granular solids was varied in the range of 1.5–3.0 g/cm^3 by consolidating 30 g of the products with the aid of the syringe and the stresses were carefully relieved at predetermined volumes. The experiment was performed first at 1.5 g/cm^3 and then repeated at 2.0 and 3.0 g/cm^3 bulk densities. The procedure was replicated three times and a total of nine samples (3 levels from each of glycerol concentration and bulk density) were obtained from the cassava and yam starches, respectively. Each sample was completely sealed in a transparent polyethylene bag of low density and kept in the refrigerator at 5 °C to prevent further hydration before subsequent experiments.

2.2. Uniaxial compression test

The Universal Testing Machine (UTM) (ZDM50-2313/56/18, Germany) was used to carry out a compression test on the bulk samples of cassava and yam starch–glycerol composites at the Federal Institute of Industrial Research, Oshodi Lagos State, Nigeria. The methods described by Carvalho et al. (2011) and Moreyra and Peleg (1980) were employed in determining the consolidation, shear and unconfined yield stresses of the composites. The experimental condition was maintained at (20 ± 2) °C and 60% (Rh) using a temperature-humidity meter for all samples during the compression.

The stress values at peak, break and yield points of compression were read from the UTM operated at the speed of 20.00 mm/min and in the loading range of 0–500 N as test conditions. During the consolidation of the granular solid sample, the vertical normal stress acts on the top of the specimen. Another kind of stress called horizontal stress acting perpendicular to the horizontal was also found to prevail and the specimen was sheared as the stress continued in an unconfined position, as is shown in Fig. 2. Neither at the top nor at the bottom of the specimen, or at the interval wall of the hollow frictionless cylinder was the shear stress found in the confined state. The compressive stress at peak gave the consolidation stress of the material under compression in a confined hollow cylindrical ring. On subsequent compression, the sample, which is now unconfined at the sides, broke at certain critical stress known as the shear stress of the sample under compression. Thus, only the vertical and horizontal stresses, which depend on the differences in the magnitude between the normal and shear stresses acting on a plane inclined by an arbitrary angle, are acting on the bulk solid at this stage. The relationships between these stresses and the normal and shear stresses acting on the plane were established from the expressions given by Schulze (2011) in Eqs. (1) and (2) as follows:

$$\sigma_{\propto} = \frac{\sigma_a + \sigma_b}{2} + \frac{\sigma_a - \sigma_b}{2}\cos(2\propto) \tag{1}$$

$$\tau_{\propto} = \frac{\sigma_a - \sigma_b}{2}\sin(2\propto) \tag{2}$$

but, with $k = \frac{\sigma_b}{\sigma_a}$, when $k = 0.6$ for cohesive granular solids like the starch materials in this case, the magnitudes of the vertical and horizontal stresses acting on the granular solid were computed, by evaluating the above equations simultaneously, from Eqs. (3) and (4) as shown below:

$$\sigma_a = \frac{5}{4}(\sigma_\alpha - \tau_\alpha \tan 2\alpha) \tag{3}$$

$$\sigma_b = \frac{3}{8}(\sigma_\alpha - \tau_\alpha \tan 2\alpha) \tag{4}$$

where $\sigma_{\propto}$ = normal stress acting on a plane inclined by an arbitrary angle (kPa), $\tau_{\propto}$ = shear stress on a plane inclined by an arbitrary angle (kPa), $\propto$ = arbitrary angle of inclination of the plane (degree), σ_a = vertical normal stress (kPa) and σ_b = horizontal normal stress (kPa).

The yield limits of the samples, which depend on their previous consolidation histories, gave greater values of the unconfined yield stress as the bulk density and the consolidation stress increased, as is shown in Fig. 3 (Schulze, 2011). The procedure was repeated three times for each of the nine samples of cassava starch–glycerol and yam starch–glycerol composites and the average values and standard deviations were computed.

2.3. Determination of flow function, frictin factor, angles of internal and wall frictions

The flow function is defined as the ratio of the consolidation to the unconfined yield stress. This was computed from the inverse of the slopes of the straight lines connecting the unconfined yield strength and the consolidation stress of cassava and yam starch–glycerol composites, as obtained from the uniaxial compression test. Additionally, the flow behaviors of the granular solids were assessed using Eq. (5), which shows the dependence of the flow function on the friction angles, consolidation and unconfined yield stresses. The flowabilities of the granular solids were characterized with respect to their flow functions according to the flow classification of bulk solids proposed by Jenike (1964), as is shown in Fig. 4 (Schulze, 2011).

$$ff = \frac{\sigma_c}{\sigma_y} = \frac{(1 + \sin\varnothing_w).(1 - \sin\varnothing_i)}{2(\sin\varnothing_w - \sin\varnothing_i)} \quad \text{(Jenike,1964)} \tag{5}$$

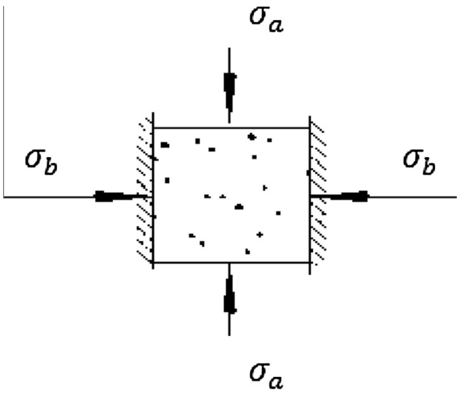

Fig. 2. Element of bulk solid sample compressed in confined state (Schulze, 2011).

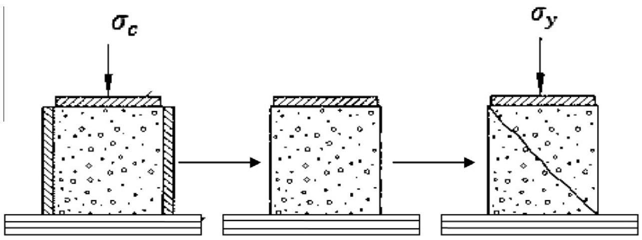

Fig. 3. Uniaxial compression test of a starch–glycerol granule (σ_y = unconfined yield stress (kPa), σ_c = consolidation stress (kPa)) (Schulze, 2011).

where *ff* = flow function, σ_c = consolidation stress (kPa), σ_y = unconfined yield strength (kPa), $\varnothing_w$ = angle of wall friction (degree) and $\varnothing_i$ = angle of internal friction (kPa).

When a granular solid is subjected to a shearing action, a characteristic relation was obtained between normal and shear stresses for the material. This relationship is often represented in graphical coordinates as Mohr diagrams. The plots of the pairs of values of consolidation and shear stresses of the cassava and yam starch–glycerol composites at different bulk densities gives straight lines with series of stress circles produced on the consolidation stress axes called the Mohr stress circle. The radius of the Mohr stress circle is equal to the unconfined yield stress of the granular solids (Chase, 2012; Peleg, 1981; Schulze, 2011; Thalberg et al., 2004). However, in order to initiate the motion within the granular solid body (plastic deformation), at least one point on the Mohr circle should correspond to a failure plane. The location of the failure plane on the Mohr circle is obtained by the tangency of the material yield locus to the Mohr circle. Consequently, the Mohr circle plays an important role in defining characteristic properties of bulk materials using yield locus. Furthermore, the angle of internal friction of the starch materials was determined from the straight lines tangent to the greater Mohr circle which defines the effective yield locus enclosing the consolidation stress axis and the angle of internal friction of the curves. Hence, the angle of internal friction was regarded as the internal friction of bulk solid at steady-state flow because the largest Mohr circle indicates the steady flow state (Jenike, 1964). The friction angle between the granular solids and the wall of a bin, which is called the angle of wall friction, was also investigated from the effective yield locus. The shear stress-consolidation stress curve with the effective yield locus, angle of internal and wall frictions of cassava starch–glycerol composite determined at 3 g/cm^3 is shown in Fig. 5. Similar curves were constructed for other composites and the angles of internal and wall frictions were measured at bulk densities of 1.5, 2 and 3 g/cm^3, respectively.

According to the experiment conducted by Jacob (2004) on the design of industrial bin and hopper, the flow behaviors of the granular solids are influenced by the magnitudes of the angle of internal friction, flow function and the friction factor accounting for the hopper half angle and the vibration in the arch thickness. Based on the established empirical relationship between these variables as expressed in Eq. (6), the friction factors of the granular solids were computed.

$$H(\theta) = ff \cdot \frac{4\sin\phi_i}{1+\sin\phi_i} \quad \text{(Jacob,2004)} \tag{6}$$

where $H(\theta)$ = friction factor accounting for the vibration in the arch thickness (dimensionless).

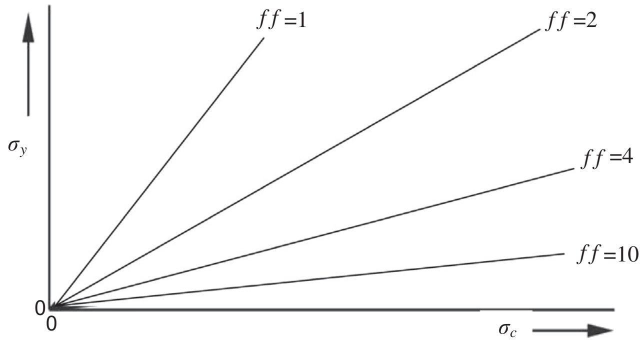

Fig. 4. Classification of flowability of granular solids as not-flowing (*ff* < 1), very cohesive (1 < *ff* < 2), cohesive (2 < *ff* < 4), easy-flowing (4 < *ff* < 10) and free-flowing (10 < *ff*) with all symbols having their usual meanings (Schulze, 2011).

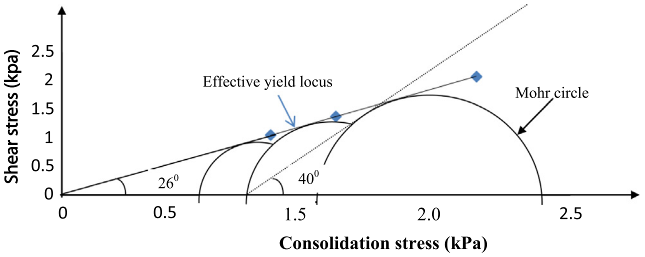

Fig. 5. Consolidation–shear stress curve of cassava starch–glycerol composite at 3 g/cm^3.

2.4. Statistical analyses

The data obtained from the uniaxial compression test were subjected to the statistical analyses using a split-split plot experiment with the compressive stress as the main factor, composite concentration as the sub factor and the bulk density as the sub-sub factor, with each having three levels in a randomized complete block design. Further analyses, using the Least Significant Difference (LSD) test, was conducted to access the level of significance at $p < 0.05$ and $p < 0.01$, respectively (Gomez and Gomez, 1984).

3. Results and discussions

3.1. Strength properties of cassava and yam starch–glycerol composites

The strength properties of the cassava and yam starch–glycerol composites at different bulk densities and glycerol concentrations are shown in Table 1. The compressive strength of the cassava and yam starch–glycerol composites significantly decreases with increasing glycerol concentration ($p < 0.05$), as is shown in Table 2. The decrease in the compressive strength can be associated with the open structures of the granular solids, whose particles are held together by van der Waal forces of attraction, at higher glycerol concentration. Therefore, as the concentration of the glycerol increases, the strengths of the resulting open structures of the granular solids decrease. And since the structures produced are not strong enough to hold the particles firmly together they will readily collapse at a lower strength of compression. This agrees with the works of Carvalho et al. (2011) and Kianmehr et al. (2012) on the mechanical properties of cassava starch based nanocomposites and the effects of compressive force, particle size and moisture content of wormy compost pellets, respectively. Carvalho et al. (2011) reported a significant decrease in the young's modulus, tensile strength and an improvement in the elongation at break with an increase in the glycerol content because of the interference of the plasticizer molecule with the starch packing, the decreasing inter-molecular attraction and increasing polymer mobility. Kianmehr et al. (2012) reported that the compressibility of the pellets increase with a decrease in the moisture content at lower loads, but the particle size did not have any significant effect on the compressibility. Moreover, as expected, the consolidation stress of the cassava and yam starch–glycerol composites is higher than its corresponding shear and unconfined yield strengths at all the glycerol concentrations. This is possibly because of the decrease in the cross sectional area of the granular solids with an increase in the vertical loads, as observed during the uniaxial compression test.

To a great extent, the strength of the granular solids does not only depend on the concentration of the glycerol, but also depends on the bulk density and the physical forces that bind the particles together. The compressive strength of the cassava and yam starch–glycerol composites significantly increases with an increase in the

Table 1
Strength properties of cassava and yam starch–glycerol composites.

Thermoplastic	ρ (g/cm^3)	Compressive strength of Starch-Glycerol Composites (kPa)								
		15 ml glycerol/100 g starch			20 ml glycerol/100 g starch			25 ml glycerol/100 g starch		
		σ_c	τ	σ_y	σ_c	τ	σ_y	σ_c	τ	σ_y
Cassava Starch	1.5	1.05 ± 0.04	1.03 ± 0.03	0.98 ± 0.03	1.00 ± 0.01	0.99 ± 0.02	0.85 ± 0.06	0.99 ± 0.01	0.98 ± 0.00	0.79 ± 0.06
	2.0	1.38 ± 0.07	1.35 ± 0.05	1.32 ± 0.07	1.36 ± 0.02	1.34 ± 0.01	1.20 ± 0.09	1.35 ± 0.01	1.33 ± 0.02	0.99 ± 0.25
	3.0	2.07 ± 0.11	2.04 ± 0.10	2.02 ± 0.08	2.09 ± 0.02	2.05 ± 0.04	1.92 ± 0.07	2.07 ± 0.00	2.04 ± 0.02	1.50 ± 0.37
Yam Starch	1.5	0.61 ± 0.01	0.59 ± 0.01	0.59 ± 0.00	0.56 ± 0.01	0.57 ± 0.01	0.55 ± 0.00	0.57 ± 0.00	0.57 ± 0.00	0.55 ± 0.01
	2.0	0.95 ± 0.02	0.93 ± 0.01	0.92 ± 0.01	0.81 ± 0.02	0.79 ± 0.02	0.76 ± 0.01	0.78 ± 0.01	0.78 ± 0.01	0.71 ± 0.01
	3.0	1.51 ± 0.02	1.48 ± 0.03	1.45 ± 0.03	1.22 ± 0.02	1.21 ± 0.03	1.18 ± 0.02	1.19 ± 0.01	1.19 ± 0.03	1.10 ± 0.07

ρ = Bulk density, σ_c = consolidation stress (kPa), τ = shear stress (kPa), σ_y = unconfined yield stress (kPa), data presented as a ± sd.

Table 2
Analyses of variance (ANOVA) of data in Table 1 from a split-split plot experiment in randomized complete block design.

S/N	Thermo plastic	Source of variation	Degree of freedom	Sum of squares	Mean square	Computed F	Tabular F	
							1%	5%
1	Yam Starch	Strength	2	0.00983	0.00492	16.378**	6.226	3.664
		Treatment	8	2.54726	0.31841	1060.7**	3.89	2.591
		Composite conc. (A)	2	2.30685	1.15342	3842.5**	6.226	3.664
		Bulk density (B)	2	0.16976	0.08489	282.77**	6.226	3.664
		Interaction (A × B)	4	0.07066	0.01766	58.846**	4.773	3.007
		Error	16	0.00480	0.00030			
		Total	34	2.56190				
2	Cassava Starch	Strength	2	0.21110	0.1055	10.97**	6.226	3.664
		Treatment	8	4.91875	0.6148	63.87**	3.89	2.591
		Composite conc. (A)	2	4.82793	2.4140	250.78**	6.226	3.664
		Bulk density (B)	2	0.07891	0.0395	4.0990*	6.226	3.664
		Interaction (A × B)	4	0.01191	0.0030	0.3092^{ns}	4.773	3.007
		Error	16	0.15401	0.0096			
		Total	34	5.28386				

CV_1, CV_2 = 6.96%, 1.94% for yam and cassava starches, respectively.
[**] Significant at 1% level.
[*] Significant at 5% level.
[ns] Not significant at 1% level.

bulk density, as was shown in Table 1. The strengths at 2 and 3 g/cm^3 were significantly higher ($p < 0.05$) than that at 1.5 g/cm^3 in all the studied samples of the starch composites, as is shown in Table 3. Thus, since at the bulk densities of 2 and 3 g/cm^3 the compressive strengths were higher, they are likely to be sufficient for the maximum compression of the granular solids. This is in line with the work of Rumpf (1962) on the strength of granules and agglomerates. He reported that the higher the bulk and particle densities of granular solids the higher the compressive strength required to form granules and agglomerates of the solids. Thus, as a rule, an increase in the density of the granular solids, at constant moisture, will ultimately increase the strength of the resulting structures. The bulk density of 3 g/cm^3 can, therefore be used in the design of hopper and other storage bins for the consistent flow of the cassava and yam starch–glycerol composites.

3.2. Flow functions of cassava and yam starch–glycerol composites

The flowability of a bulk solid depends on its unconfined yield strength, consolidation stress and by extension its flow function. The greater the flow function of a bulk solid, the better its flowability in a specific piece of equipment. The flow functions of the cassava and yam starch–glycerol composites are shown in Figs. 6 and 7. It can be said that, since the consolidation stress increases with an increase in the unconfined yield strength, any increase in the yield strength will also increase the flow function of the granular solids. And since the granular solids flow with an increase in the consolidation stress, there must exist a material-specific yield limit for them. The materials are expected to flow incipiently or undergo plastic deformation because of the increasing volume accompanying the increase in the unconfined yield strength. These are evident

Table 3
LSD test of significance of stress values of cassava and yam starch–glycerol composites.

S/N	Thermoplastic	Bulk density (kg/m^3)	Mean stress of composite (kPa)					
			15 ml glycerol/100 g starch		20 ml glycerol/100 g starch		25 ml glycerol/100 g starch	
1	Yam Starch	1.5 (Control)	0.5982	–	0.5595	–	0.5632	–
		2	0.9351	0.3369**	0.7863	0.2268**	0.7543	0.1911**
		3	1.4794	0.8812**	1.2018	0.6423**	1.1587	0.5955**
2	Cassava Starch	1.5 (Control)	1.0193	–	0.9468	–	0.9206	–
		2	1.3495	0.3302**	1.2993	0.3525**	1.2272	0.3066**
		3	2.0419	1.0226**	2.0202	1.0734**	1.8702	0.9496**

$LSD_{0.05}$ = 0.0565, $LSD_{0.01}$ = 0.0779 (Cassava starch), $LSD_{0.05}$ = 0.00999, $LSD_{0.01}$ = 0.01377 (Yam starch).
[**] Significant at 5%.

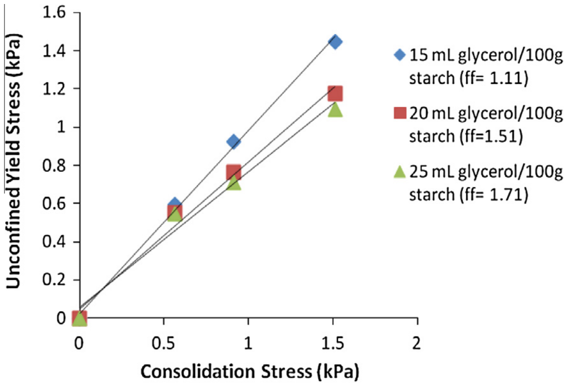

Fig. 6. Flow function of cassava starch with glycerol variability.

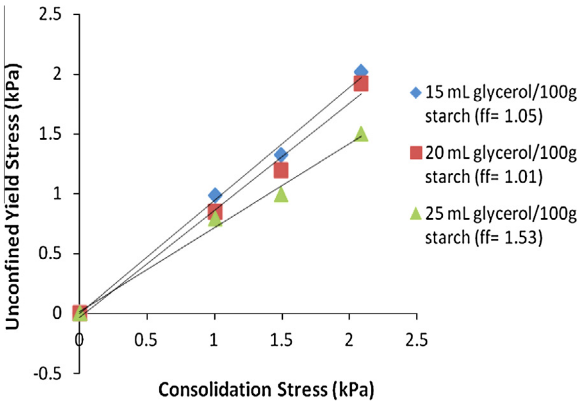

Fig. 7. Flow function of yam starch with glycerol variability.

in the work carried out by Peleg (1978) on the flowability of food powders and methods of their evaluation. He stated that the flowability of most food powdered materials increases with an increase in the flow function.

Also, according to the results in Figs. 6 and 7, the flow will be difficult for the material whose flow function is relatively lower than the others. The free flowing of a starchy material is nearly impossible because of its high cohesion. For this reason, the material which has the easy flow is 25 ml glycerol per 100 g starch composites among the studied samples. Obtaining the easiest flow for 25 ml glycerol per 100 g starch composites can be attributed to the even distribution of the glycerol molecules through the porous matrix of the granular solids. The flow can also be related to a likely increase in the particle size as a result of increasing glycerol concentration thereby leading to the increased cohesive force among the individual starch molecules (Schonlebe and Seewald, 1994). At this point, it can be said that large particle size has an adverse effect on the material flow. This buttresses the fact contained in the work of Thalberg et al. (2004) on the comparison of different flowability tests of powders for inhalation. They stated that contrary to the difficult flows in most granular solids, the higher flow function and lower force of cohesion in most powders are evidence of their higher flowabilities. It is paramount to understand that free moisture exists in the beds of the granular solids in the forms of liquid and solid bridges occurring between the individual particles (Schepky, 1986). Thus, the cohesion in the starch–glycerol composites involves the liquid bridges and may also involve the solid bridges between the particles. The connections of the liquid bridges depend on the glycerol content and its distribution. The contributing factors are the interfacial tension and the capillary pressure. An expansion in the number of the solid bridges can result in the increased cohesion and aggregation and, ultimately, the formation of a hard cake. Caking is the state in which the granular solids cannot be moved by vigorously shaking or tapping the container (Dawoodbahai and Rhodes, 1989; Nokhodchi, 2005). The caking process is caused when the glycerol becomes hydrated on the particles' surfaces. The resulting hydration causes crystallization and the deposition of solid bridges between particles (Burak, 1986). The flow equations of the cassava and yam starch glycerol composites, which were obtained from the samples with the highest flow function and cohesion, are given in Eqs. (7) and (8), as follows:

$$\sigma_{csgr} = 0.7022\sigma_c + 0.0169 \quad ff = 1.53 \tag{7}$$

$$\sigma_{ysgr} = 0.7095\sigma_c + 0.0575 \quad ff = 1.73 \tag{8}$$

where σ_{ysgr} = unconfined yield stresses of yam starch–glycerol composite (kPa), σ_{csgr} = unconfined yield stresses of cassava starch–glycerol composite (kPa) and the other symbols have their usual meanings.

A typical application of the flow function as a material characteristic in the food industry is the quality assessment of granular solids (Bell et al., 1994). Fitzpatrick et al. (2004) determined the flow properties of thirteen granular solids of various particle sizes, moisture contents, bulk densities and particle densities and concluded that the particle size distribution and the moisture content markedly influenced the flowability, but no strong enough relationship was found to relate the flowability of the materials based solely on these physical properties. It was also stated that the surface forces between the particles influence flowability to a larger extent. Schonlebe and Seewald (1994) reported that the flowability of most powdered materials increased with increasing force of cohesion between the individual particles. Hence, based on these, it can be established that the flow function of the granular solids will largely depend on both the particle size diameter and the cohesive force between the particles. This physical approach can be used for modern data evaluation of the flow functions of several granular solids with respect to their particle size distribution and the material properties (Tomas, 2004). The flow functions can also be used in the characterization of flowability of the cassava and yam starch–glycerol composites and in the design of the handling and processing equipment for the products.

3.3. Friction angles of cassava and yam starch–glycerol composites

The friction angles, which describe the flow properties of the starch–glycerol composites, were determined from their yield locus. The consolidation stress was equal to the major principal stress of the Mohr stress circle and is tangential to the yield locus, as was shown in Fig. 5 (Schulze, 2011). Obviously, the yield locus represents the shear stress in the granular solids at the end of the steady-state consolidation, as is usually the case in the shear test, in the uniaxial compression test. The analogy with the shear test was made here to better explain the relevance of yield locus in defining the shear stress and friction angles of the granular solids not minding the fact that a uniaxial compression test usually results in smaller unconfined yield strength (Schulze, 2011).

The influence of the bulk density on the angle of internal friction is shown in Fig. 8. The angle of internal friction is a measure of the force required to cause the particles to move or slide against each other. The angles of internal friction between the individual starch molecules generally increase with an increase in the bulk density in the range 1.5–3 g/cm^3. However, the angle of internal friction, at all the bulk densities considered, was higher in the cassava than in the yam starch–glycerol composites. The softer

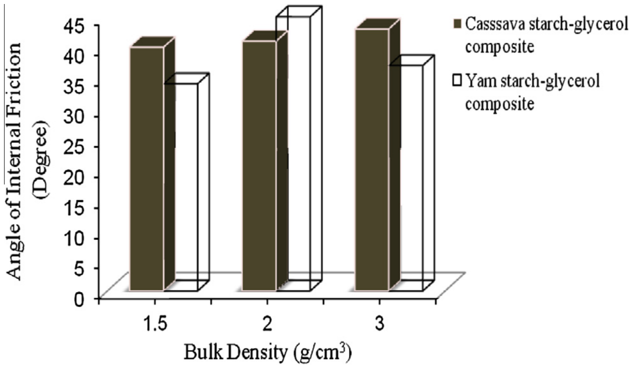

Fig. 8. Influence of bulk density on angle of internal friction.

the individual particle contacts, the larger are the differences between these friction angles and consequently, the more cohesive is the response of the granular solids. This agrees with the findings of Çagli et al. (2007) in their work on the flow property measurement, using the Jenike shear cell, for seven different bulk solids. They reported that there is no significant difference between the angles of internal friction values of the bulk solids and their stress levels due to the increasing cohesion values at higher stress and particle density. It is worthy to note that the angle of internal friction is not the same thing as the angle of repose and so should not be used, interchangeably, in design. Many of the earlier bin designs were wrongly based upon the angle of repose instead of angle of internal friction; but this alone is not sufficient to account for all of the mechanisms affecting the bin performance on more cohesive solids. The angle of repose is only useful in determining the contour of a pile, and its popularity among engineers is not due to its usefulness but due to the ease with which it can be measured (Chase, 2012; Thalberg et al., 2004). Therefore, the angle of internal friction data is needed for calculating the lateral pressure on the walls of storage bins and for the design of the gravity flow hopper (Ortega-Rivas, 2003). The angle provides information on the design of conveyors used to remove bin discharge, and of loading device for granular solids (Peleg, 1981). Also, the angle of internal friction is required in the design of hopper and silo for the handling and processing of bulk solids (Jenike, 1964; Fitzpatrick et al., 2004).

The influence of bulk density on the angle of wall friction is shown in Fig. 9. The wall friction is the friction between a bulk solid and its surface, especially the wall of a hopper. The angle of wall friction of the cassava and yam starch–glycerol composites was found to be inconsistent with increasing bulk density from 1.5 to 3 g/cm^3. This is possibly because of the increasing friction between the starch molecules and the surface of the solids. In a related investigation, Savage (1967) carried out an analysis of the gravity flow of cohesion-less bulk solids in a vertical converging channel and observed that the wall friction was more influential than the angle of internal friction in reducing the flow rate for small values of the cone wall half angle. Similarly, Bumiller et al. (2012) reported that the lower the angle of wall friction, the lesser the steepness of the hopper wall for consistent flow of material along it. The coefficient of wall friction angle is not only important for the design of silo for flow and strength, but also for the design of chutes and other equipment, where the bulk solid will flow across a solid surface. It is possible to decide whether or not the polishing of the wall surface or the use of a liner would have advantages in the flow of the bulk solid with prior knowledge of the wall friction angle (Schulze, 2011). Hence, in this work, the higher angle of wall friction at 3 g/cm^3 is required in the design of hopper or silo, with steeper walls, for the consistent flow of the granular solids.

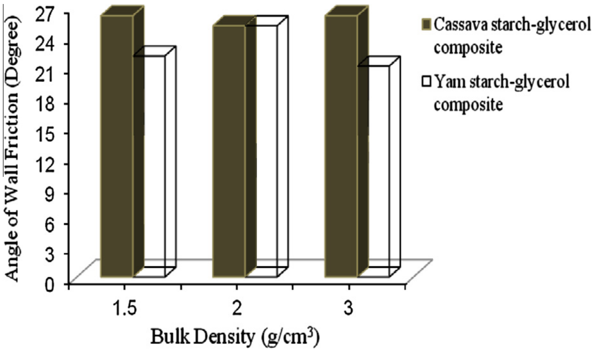

Fig. 9. Influence of bulk density on angle of wall Friction.

3.4. Flow properties of cassava and yam starch–glycerol composites

The flow properties of cassava and yam starch–glycerol composites at different bulk densities are shown in Table 4. The half angle of the cassava and yam starch glycerol composites was obtained from the pairs of angles of the internal and wall frictions using the conical hopper design chart (Jacob, 2004). It is worth noting that many of the problems associated with the hopper design, such as arches and rat-hole formation, can be avoided by designing the hopper to operate in the required cone angle of the range of 40–0° from the vertical axis (Chase, 2012). Furthermore, a rule of thumb of 70° hopper angle (corresponding to 35° hopper half angle) is often used for achieving the mass flow of an ideal powder. There is also the possibility of this requirement reducing by 10–12° upon changing from a conical to a wedge hopper (Marinelli and Carson, 1992). Therefore, with the mean half angle of the cassava and yam starch–glycerol composites as 18.3° and 23.0°, the design of the hopper, silo or conveyor for the handling and processing of the granular solids can conveniently be made possible.

The actual consolidation stresses of the cassava and yam starch–glycerol composites, which are computed from Eqs. (7) and (8) is shown in Table 4. Generally speaking, the actual consolidation stress increases with an increase in the bulk density of the starch–glycerol composites. The hydrating effects of the glycerol, inducing time consolidation with increasing bulk density in the unconfined state, are not unconnected with the increased actual consolidation stress of the starch–glycerol composites. However, it should be noted that the actual consolidation stress of the starch containing above 15 ml glycerol brought about a little drop in the cohesion and consequently the average unconfined yield stress of the composites. It is likely that the high amount of glycerol in the starch interfered with the flow properties of the resulting composites due to the significant increase in the water absorption or hydrating effect of the starch–glycerol composite. Peleg (1981) reported that under low compression load, which may exist during powder storage, the relationship between the bulk density and the stress usually obey an empirical logarithmic relationship. Thus, a simultaneous increase in the bulk density with a corresponding increase in the actual consolidation stress can indicate the extent of the powder's cohesiveness. In fact, this could cause the formation of arches and rat-holing in the handling equipment if not checked at certain bulk density. Modern hoppers and silos are often designed at lower consolidation stress and bulk density of material in order to increase flowability of the equipments while addressing this kind of flow problem (Tomas, 2004).

The friction factor accounting for the hopper half angle, vibration in the arch thickness and the geometric configuration of cassava and yam starch–glycerol composites is also shown in Table 4. The friction factor of the cassava starch–glycerol composite generally increased with increase in the angle of internal friction, but the

Table 4
Flow properties of cassava and yam starch–glycerol composites.

Composite and flow function	Flow properties	Unit of measurement	Bulk density (g/cm^3)		
			1.5	2.0	3.0
Cassava Starch-G (ff^h = 1.53)	σ_{csgr}	kPa	0.88	1.17	1.81
	σ_c	kPa	1.22	1.64	2.56
	θ	degree	18.0	19.0	18.0
	$H(\theta)$	–	2.39	2.42	2.48
Yam Starch-G (ff^h = 1.73)	σ_{csgr}	kPa	0.56	0.80	1.24
	σ_c	kPa	0.71	1.04	1.67
	θ	degree	25.0	19.0	25.0
	$H(\theta)$	–	2.48	2.87	2.60

σ_{csgr} = Average yield stress, σ_c = actual consolidation stress, θ = hopper half angle, $H(\theta)$ = friction factor, G = glycerol, ff^h = flow function of 25 ml glycerol/100 g starch.

factor remains inconsistent for the yam starch–glycerol composite. It is quite certain that the increased friction factor of the former was because cassava starch granules are geometrically one-dimensional. The inconsistency in the values of the friction factor of the latter can be associated with the non-uniformity in the particle size of yam starch granules causing its bulk density to become unsteady. These corroborate the studies by Fatah et al. (1998) and Fatah and Sanchez-Calvo (2004) on the particle size of cohesive powders where they reported the existence of two categories of granular sizes as micronics (with particle size ⩽50 μm) and nanometric (with particle size ⩽500 nm) in most powders. They also reported that the nanometric particles are more complex and show a different behavior from the micronic particles under the action of the variation of the external forces. The complexity of this behavior is due to the smaller size of the nanometric particles which tends to form agglomerates of completely random size and shape by the action of the inter-particle forces between the primary particles. Hence, the higher surface to volume ratio and the shorter distances between the particles of the granular solids affect their flow properties (Turki and Fatah, 2008).

4. Conclusions

An understanding of the flow and strength properties of the granular solids is required in the design hopper and other handling and processing equipment in the food industry. The quantitative information regarding flowability of the granular solids is also required as part of comparative tests and quality control. With adequate data on the properties of a granular solid at hand, the design of handling equipment, free from arch and rat-hole formations at the discharge end, can be achieved. Thus, the strength and flow properties of cassava and yam starch–glycerol composites were investigated in this research, for their application in the design of storage bin, for handling and processing of granular solids, in the food industry.

The compressive strength of cassava and yam starch–glycerol composites, which include the consolidation, shear and unconfined yield stresses, increased significantly with an increase in the bulk density and a decrease in the glycerol concentration ($p < 0.05$). This was because of the hygroscopic character of the glycerol, which leads to the increase in the free volume and cohesion of the system. The increased cohesion of the system indicates the likelihood of increasing flowability of the granular solids as they are handled in the storage bin. Also, the strengths at 2 and 3 g/cm^3 were significantly higher ($p < 0.05$) than that at 1.5 g/cm^3 in all the studied samples of the starch composites. This implies that the bulk densities of 2 and 3 g/cm^3 are likely to be sufficient for maximum compression of the granular solids. Thus, the bulk density of 3 g/cm^3 can be used in the design of the storage bin. Moreover, the flow functions of the granular solids vary in the range 1.05–1.53 and 1.11–1.73 with an increase in the glycerol concentration. The cohesiveness of the composites was higher at 25 ml glycerol per 100 g starch concentration. The hopper half angle, friction factor and angles of internal and wall frictions of cassava and yam starch–glycerol composites generally increase with increasing bulk density. The higher angle of wall friction at 3 g/cm^3 requires that the hopper wall be steep enough to allow more composites to flow. In practice, however, sufficient force should be provided, if correctly designed, to break the arches and rat-holes whenever they form in a storage bin; because of the possibility of the flow stopping or becoming intermittent during discharge from the structure.

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