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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

A. Fadeyibi [a,*], Z.D. Osunde [a,1], G. Agidi [b,2], E.C. Evans [c,3]

[a] Department of Agricultural and Bioresources Engineering, Federal University of Technology Minna, Nigeria
[b] Engineering Department, National Cereal Research Institute Badegi, Niger State, Nigeria
[c] Department of Biochemistry, Federal University of Technology Minna, Nigeria

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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

* Corresponding author. Tel.: +234 7034867681/8034537068.
E-mail addresses: adeshinaf601@gmail.com (A. Fadeyibi), zinashdo@yahoo.com (Z.D. Osunde), evanschidi@gmail.com (E.C. Evans).
[1] Tel.: +234 8034537068.
[2] Tel.: +234 8036772988.
[3] Tel.: +234 706580944.

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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).

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.

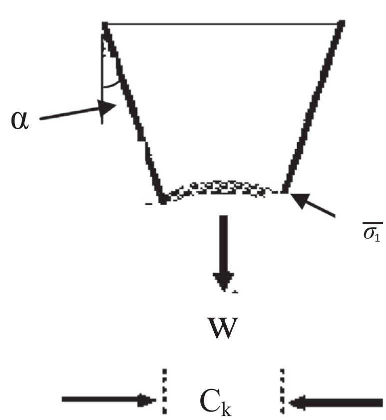

Fig. 1. Forces acting within the hopper to prevent stable arch formation ($\sqrt{\sigma_1}$ = consolidated stress generated in an arch at the outlet (kPa), W = weight of the discharged granular solid (N), α = hopper half angle (degree) and C_k = hopper outlet size (m)) (Schulze, 2011).

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