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Simultaneous measurement of rice grain friction coefficient and angle of repose using rotating cylinders

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Summary

Several methods have been developed to measure the friction coefficient of grains and seeds as well as their angle of repose, independently. However, it seems that one single method capable of simultaneous measurement of these two important parameters of grain products is of importance. In this study, simultaneous measurement of brown rice grain friction coefficient and angle of repose is performed by using rotating cylinders method. The effects of rotational speed, cylinder diameter and filling degree on rice grains, also lower and higher angle of repose along with their friction properties were considered. Results showed that proper speed for reaching slumping and rolling motions depends on cylinder diameter and filling degree varying from 0.5 to 9.7 rpm and 2 to 34.6 rpm, respectively. An insignificant difference in the range of 1° to 4° was observed between lower and upper angles of repose which indicates the reliability of the proposed method to determine the dynamic angle of repose. Results also revealed that rotational speed of cylinders did not significantly affect the lower and upper angles of repose; however, they were not affected by filling degree. Finally, the friction coefficient of rice grains was affected by cylinder diameter and filling degree. The findings of this study may be applied in the design and mathematical modeling of grains' motions in rotary dryers, mixers, and silos.

Keywords: rotating cylinders, friction coefficient, angle of repose, filling degree.

Introduction

Rice is one of the most important agricultural products around the world having an central role in human nutrition. Storage, handling, and processing of rice grains are challenging, especially when considering minimization of product loss and maintaining grain quality during the storage.

Rotary drums with internal flights are widely used in food, mineral, and pharmaceutical industries for drying, mixing, coating, or chemical reaction processes (ZHANG et al., 2018; HE et al., 2019). Using rotary cylinder is a rather new method to measure both static and dynamic angles of repose and wall friction coefficient. Two other angles, i.e., lower and upper angles of repose can also be determined through this method. Measurements of these angles along with internal friction coefficient of grains and friction coefficient between grains and wall are useful in mathematical modeling of grains' motions in rotary dryers, mixers and silos (HELDER et al., 2006).

With a rotating drum half-filled with uniform sediment grains, three different angles of repose are clearly identified. They are the upper angle of repose formed at the inception of an avalanche, the lower angle of repose at the end of an avalanche, and the dynamic angle of repose characterized with continuous sediment transport down the slope. The study suggested that the different angles of repose should be treated with caution when applying in investigations of bedload transport, dune migration and local scour development (CHENG et al., 2017).

Research indicates that Angles of repose of grains are related to the slipping and rolling properties, specific weight, size and shape of the grains. These angles increase by increasing the slipping and rolling friction coefficient and decreasing the grains sphericity. However, they decrease when the size of the grains exceed a threshold value. The results of these research also show that under the present simulation conditions, the angle of repose is significantly affected by the sliding and rolling frictions, particle size and container thickness, and is not sensitive to density, Poisson's ratio, damping coefficient and Young's modulus. Increasing rolling or sliding friction coefficient increases the angle of repose, while increasing particle size or container thickness decreases the angle of repose. Based on the numerical results, empirical equations are formulated for engineering application. The proposed simulation technique and equations are validated by comparing the physical and numerical experiments, where focus is given to the effects of particle size and container thickness (HELDER et al., 2006; ZHOU et al., 2002).

Several studies have been carried out to determine the static and dynamic angles of repose, lower and upper angles of repose, and wall friction coefficient for industrial materials (SPURLING, 2000; MELLMANN, 2001; ARANSON and TSIMRING, 2006). However, search reviews in bibliographic databases reveal that the simultaneous measurement of static and dynamic angles of repose, wall friction coefficient, and lower and upper angles of repose via rotating cylinders for agricultural grains may not be fully studied by researchers especially for a grain similar to brown rice.

The objective of this study was: (a) to simultaneous measurement of brown rice grain friction coefficient and angles of repose via rotating cylinders, and (b) to investigate the effects of cylinder diameter, rotational speed and filling degree on friction coefficient, static, dynamic, lower, and upper angles of repose of the grains.

According to the literature, two types of angles of repose have been investigated, i.e., static and dynamic angles of repose which can be measured using several methods. In the most common method, which is called piling method, grains flow onto a circular plate from a certain height. Static slope angle (Φ_d) is measured using Eq. (1)

$$\Phi_d = \arctan\,(2\,H\,/\,D_h) \tag{1}$$

where H is the height in m, and D_h is the diameter of the cone surface in m (JOSHI et al., 1993; KINGSLY et al., 2006). In another method which is called emptying method, grains are poured out through an outlet at the side of a container. The gradient of the grains inside the container is considered as the angle of repose (KHAZAEI and GHANBARI, 2010; JAIN and BAL, 1997; KARABABA, 2006).

A conventional method to determine the friction coefficient is the use of materials on an adjustable tilting surface. In this method, a hollow cylinder, open at both ends, is filled with the testing material and is placed on an adjustable tilting surface. The angle of the surface gradually increases until the materials inside the cylinder start to slip

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down the surface. The static friction coefficient equals to the tangent of the surface angle (KHAZAEI and GHANBARI, 2010).

In rotary cylinders, to measure the angle of repose and friction properties, the material is poured (up to the half) into the cylinder. By increasing the rotational speed, several types of movement are identified, namely, slipping, slumping, rolling, cascading, cataracting and centrifuging (Fig. 1) (MELLMANN, 2001). The material behavior in rotary cylinder depends on various parameters, such as cylinder rotational speed, cylinder diameter, filling degree, particle size and grain shape (HENEIN et al., 1983; MELLMANN, 2001; SPURLING, 2000).

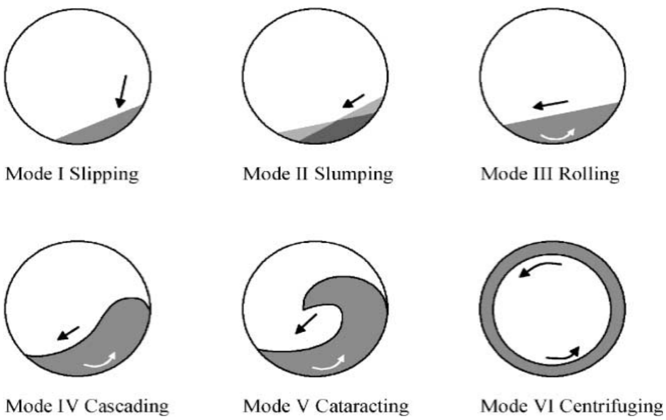

Fig. 1: Transverse motion modes of materials in a rotating cylinder (KHAZAEI and GHANBARI, 2010).

Two principal criteria for evaluating the material modes of operation are characterized in rotating cylinders: filling degree (Eq. 2) and Froude's number (Eq. 3) (INGRAM et al., 2005; LIU et al., 2006).

$$f = (1/\pi) \times (\varepsilon - \sin\varepsilon \cos\varepsilon) \qquad (2)$$

$$Fr = \omega^2 R / g \qquad (3)$$

where f is the filling degree of cylinder, ε is the filling angle which corresponds to the half bed angle of the circular segment occupied with material, Fr is Froude's number, ω is the angular speed of cylinder in rad/s; R is the cylinder radius in m, and g is the gravitational constant in m/s^2.

Transition from one mode to another occurs due to the changes in cylinder rotational speed and cylinder filling degree.

In low speeds or lower filling degrees, slipping mode occurs which is an undesirable behavior. In this motion, materials move as fluid inside the cylinder with no particle mixing. This motion mode should be prevented by rough walls or attaching sandpaper to the wall.

In general, measuring the angles of repose for solid materials in rotating cylinders occurs in the slumping motion (MELLMANN, 2001). In this motion mode, the materials are lifted by the rotating cylinder wall to reach the upper angle of repose (β) at which grains are began to slide down and inclined to the horizontal by the lower angle of repose (α) (LIE et al., 2005a, 2005b). α is also called natural angle of repose (ARANSON and TSIMRING, 2006).

A detailed analysis of the α is brought by MELLMANN (2001) and LIU et al. (2005b) who studied α in slumping motion. As a result, they found that friction coefficient of grains to the wall (μ) can be calculated by Eq. (4):

$$\mu = \tan\alpha \qquad (4)$$

In slumping motion, the material bed is lifted until it reaches β angle. At the upper point, particles begin to slide down in the form of an avalanche inclined to the horizontal to reach α (Fig. 2a). By increasing the cylinder rotation speed, time intervals between two avalanches decreases and a continuous flowing happens which is called rolling motion. According to MELLMANN et al. (2004) and LIU et al. (2006), the slope of the bed surface is remained nearly constant which is called dynamic angle of repose (θ) (Fig. 2b). Dynamic angle of repose (q) is defined using Eq. (5).

$$\theta = \frac{\alpha + \beta}{2} \qquad (5)$$

By increasing the speed, cascading motion occurs. The transition from rolling to cascading depends on both the rotational speed and particle size (SPURLING, 2000). Slumping mode occurs in rotational speeds lower than 3% of standard speed in which the centrifuging motion happens. However, rolling and cascading modes often occur in moderate speeds, between 3% and 30% of the speed where centrifuging motion happens (HENEIN et al., 1983). According to MELLMANN (2001), standard speed in which the centrifuging mode occurs (n_c) can be calculated by Eq. (6).

$$n_c = \left(\frac{30}{\pi}\right)\sqrt{\frac{g}{R}} \qquad (6)$$

where R is the cylinder radius in m, and g is the gravitational constant in m/s^2. Centrifuging motion often occurs in speeds more than n_c. In this mode, grains on the outer paths begin to adhere to the wall as a uniform film. Therefore, friction coefficient and angles of repose are studied in slumping and rolling motion modes (HENEIN et al., 1983).

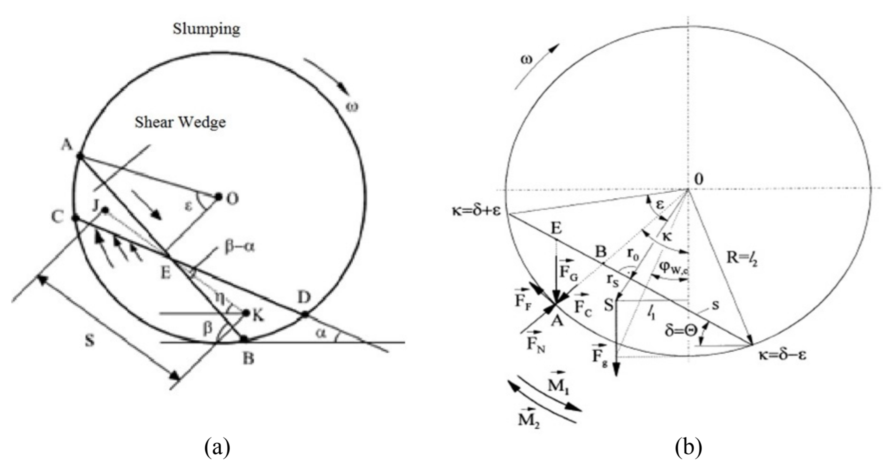

Fig. 2: (a) Material bed motion in slumping mode, and (b) material bed motion in rolling mode.

Materials and methods

Materials

Rice grains were grown and harvested in a research farm in Guilan (a Province of Iran), in 2019. The grains were cleaned manually to remove all foreign material and broken grains. The initial moisture content of the grains was 7.5% (w.b.). Samples with higher moisture content were prepared by adding distilled water to the grains, according to the equation reported by KINGSLEY et al. (2006). The prepared samples were held in polyethylene bags and stored at 5° C in a refrigerator for 48h before using them for the experiments. The physical dimensions of the rice grains were determined by taking 200 grains randomly and measuring the grains linear dimensions (length, width, and thickness) using a micrometer reading to 0.01 mm. For each grain, the geometric mean diameter, sphericity, volume, and surface area were determined using the equations reported by AL MAHASNEH and RABABAH (2007) and BARYEH and MANGOPE (2003). The bulk density, true density, porosity and 1000 grainmass were also determined according to the methods proposed by KINGSLY et al. (2006). The experimental setup, simultaneously, determined the μ and angles of repose of the rice grains via rotating cylinders. A device with three horizontal rotating cylinders with diameters equal to 15, 20, and 30 cm was used for the experiments (Fig. 3). Each cylinder was made of polyethylene having a transparent glass plate at the front for visual observation. Rotational speed of the cylinders was adjustable varying from 0.50 to 100 rpm and the filling degree of cylinders ranged from 7 to 46% of the total volume of cylinder. To avoid unwanted sliding motion, the inner walls of the cylinders were glued with sandpaper (SPURLING, 2000; INGRAM et al., 2005).
During the experiments, material behavior was recorded by a 100-fps digital Canon-PC1210 camera with 10 Megapixel resolutions which was installed perpendicularly to the plane of the glass plate.

Fig. 3: The device used in this study which was established by GHANBARI (2008).

Methods

In the beginning of the experiments, each of the partially filled cylinders was rotated at 0.5 rpm. Then, the speed gradually increased to reach the slumping or rolling motion. This process was recorded by the camera and then, images were extracted from video by Windows Movie Maker software. Images were used for the direct measurement of α and β in slumping mode and q in rolling mode using Eq. (5). Meanwhile, μ of rice grains was calculated using Eq. (4). The experiment was carried out for all three cylinders with four replications.
Since both α and the motion behavior of the grains depend on their physical properties including size, shape and density. Therefore, physical dimensions including length, width and thickness were measured for randomly selected 100 grain samples with a 0.01 mm accuracy micrometer. Other physical dimensions were calculated using the equations available in MOHSENIN (1986), BARYEH and MANGOPE (2002), and KINGSLY et al. (2006). Obtained values are brought in Tab. 1.
In this study, the results of angles of repose obtained in cylinder rotating approach were compared with those obtained by piling and emptying methods, described in Section 2. For the piling method, grains were flowed onto a horizontal surface through a funnel. Then, d and H of the formed cone were measured and Φ_d was calculated using Eq. (1). In the emptying method, grains were poured out through a 25 × 25 × 20 cm outlet in front of a container. The gradient of the grains inside the container was determined as the static angle of repose (JAIN and BAL, 1997; KHAZAEI and GHANBARI, 2010; KARABABA, 2006).
Furthermore, the friction coefficient measured in this study was compared to the result obtained by the tilting method described in Section 2. In the tilting method, grains were poured into a hollow cylinder with a length of 80 cm and 50 cm in diameter and open at both ends which was placed on an adjustable tilting surface. The method of measurement is brought in Section 2.

Tab. 1: Dimensional characteristics of rice grains

Dimension	Mean	Standard Deviation
Length (mm)	7.94	0.46
Width (mm)	1.89	0.10
Thickness (mm)	1.72	0.09
Geometric Mean Diameter (mm)	2.96	0.90
Sphericity	0.37	0.01
Surface Area (mm^2)	27.60	1.82
Volume (mm^3)	13.66	1.33
1000 Grain Mass (g)	20.31	0.004
Density (g/mm^3)	0.72	0.13

Results and discussion

Fig. 4 depicts filling degrees at different rotating speeds in slumping, rolling, and cascading modes for cylinders with diameters of 15, 20, 30 cm. This figure shows that the slumping and rolling modes occurred in the range of 0.5 to 3 rpm with $Fr = 4.27 \times 10^{-5}$ and 2 to 30 rpm with $Fr = 0.68 - (1.53 \times 10^{-3})$, respectively in the largest cylinder. These parameters were in the range of 0.5 to 2.6 rpm with $Fr = 2.51 \times 10^{-5}$ and 2 to 38 rpm with $Fr = 4.02 - (6.79 \times 10^{-4})$ for the cylinder with 20 cm diameter. And for the smallest cylinder, they ranged from 0.5 to 9.7 rpm with $Fr = 2.06 \times 10^{-5}$ and 8.6 to 34.6 rpm with $Fr = 4.89 - (7.77 \times 10^{-3})$.
As a result, by increasing the cylinder diameter for a constant filling percentage of grains, the rotation speed for transition from slumping to rolling motion effectively increased. Similar results have been reported by LIU et al. (2005a) and CRISTO et al. (2006) for coffee beans, grains gravel, sand and limestone grains. In fact, the transition from slumping to rolling mode depends on cylinder rotational speed, friction coefficient of grains to wall, cylinder filling percentage and materials physical properties (MELLMANN, 2001).
The effects of the filling degree on β is reported for rice grains during slumping motion in Fig. 5. As discussed in Section 3, it is necessary to use the slumping motion to determine angles of repose. Accordingly, it is essential to determine the rotational speed and percentage of filling degree for achieving slumping and rolling motion for rice grains. Based on MELLMANN (2001), ARANSON and TSIMRING (2006), and LIU et al., (2005a), α equals to static angle of repose and

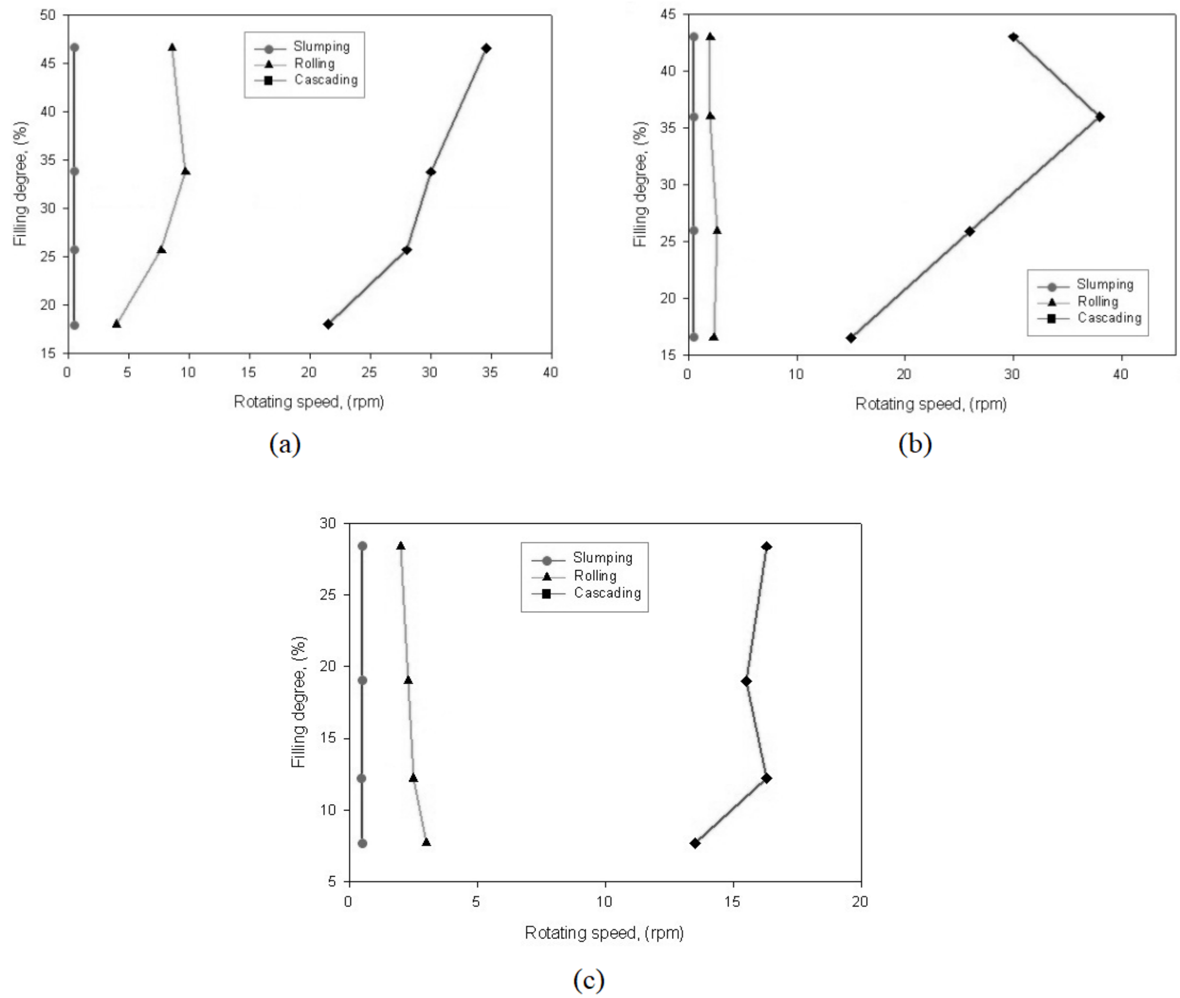

Fig. 4: Filling degree at different rotating speeds in slumping, rolling, and cascading modes for cylinders with diameters equal to (a) 15 cm, (b) 20 cm, and (c) 30 cm.

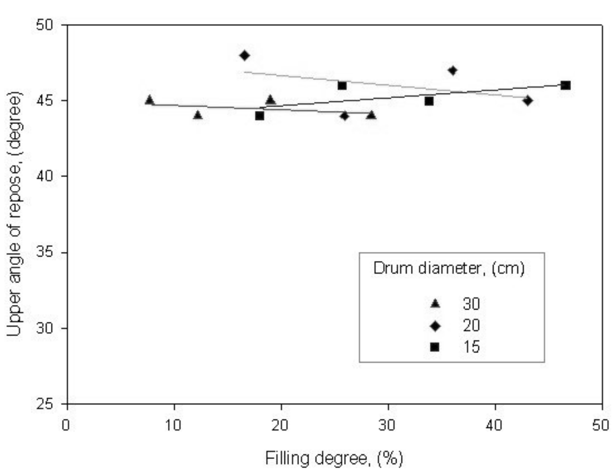

Fig. 5: Effect of filling degree on upper angle of repose for cylinders with diameters equal to 15, 20, and 30 cm.

also, tangent of this angle equals to grains to wall friction coefficient. According to the figure, in the smallest cylinder, filling percentage had slight effect on β. However, for both the medium and the largest cylinders, this effect was higher. α and β ranged from 40° to 46° and 44° to 48°, respectively. LIU et al. (2006) determined that β for steel balls and fertilizer pellets was 34.97° and 40.7° degrees, respectively. HENEIN et al. (1983) obtained β for 15 industrial materials and reported values more than 32°. KHAZAEI and GHANBARI (2010) studied the effects of rotary cylinder parameters on α and β of wheat grains and showed that these angles vary from 27° to 33° and 33° to 37°, respectively.

According to Fig. 6, cylinder rotational speed had effective effects on α and β. Also, the effect of different filling degrees and cylinder diameters on these parameters appeared to be effective, ranged from 1° to 4°. Similar results are reported by LIU et al. (2005b) for industrial materials. Also, DAVIDSON et al. (2000) reported the range of 2° to 4° for α and β in sand with mean diameter of 4 mm.

Fig. 7 shows that the calculated θ for rice grains using Eq. (5) were in the range of 42° to 47° at different cylinder diameters and filling degrees. According to the figure, filling degree has decreasing effects on θ in cylinders with 20 and 30 cm diameter; however, θ increases by increasing the filling degree for cylinder with 15 cm diameter. Meanwhile, the diameter of the cylinder has also effective effects on θ. Using prevalent methods for wheat grains, TABATABAEEFAR (2003) found that increasing the moisture content of 8-22% increased θ from 37° to 45°.

Results showed that both measured and calculated dynamic angle of repose (θ) in three different methods were effectively different (Tab. 2). The difference between the values from rotating cylinders and emptying method was between 16-17°. In addition, the difference between the values from rotating cylinders and emptying methods

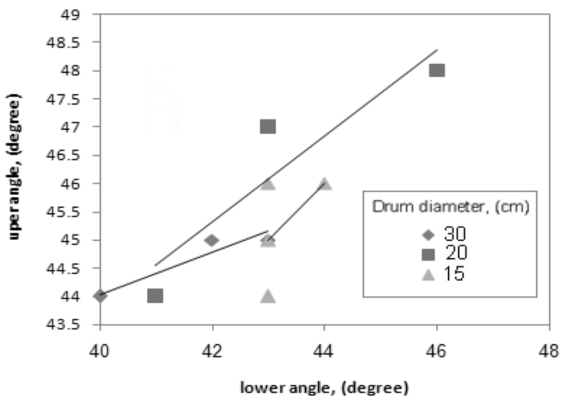

Fig. 6: The differences between lower and upper angles of repose in rice grains due to different filling degrees and cylinder diameters ranges from 1° to 4°.

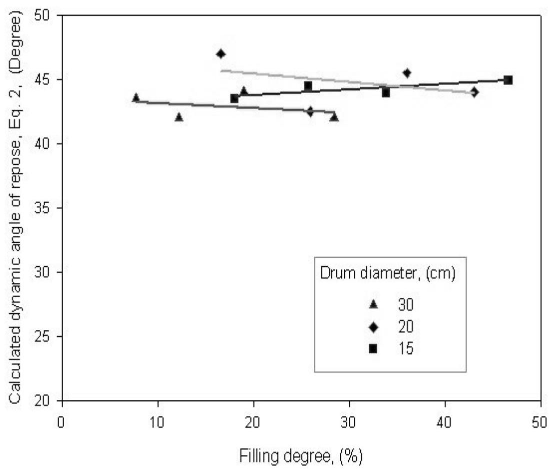

Fig. 7: Effects of filling degree on calculated dynamic angle of repose using Eq. (5) for cylinders with diameters equal to 15, 20, and 30 cm.

with piling method were 1-15°. The difference between methods may be due to difference in grain mass and method apparatus.

Based on the results of this study, friction coefficient of rice grains to a wall surface covered with sandpaper, depends on filling degree and cylinder diameters (Fig. 8). According to this figure, for cylinders with 30 and 20 cm diameters, filling degree had decreasing effect on wall friction coefficient; however, friction coefficient increased by increasing the filling degree for the cylinder with 15 cm diameter. Results from these experiments showed effective differences for the average friction coefficient obtained from rotating cylinder and tilting method (Tab. 3).

The results in Tab. 4 demonstrate dynamic angle of repose in rolling mode for rice grains. These results suggest that the Eq. (5) is reliable enough to measure θ by using α and β in slumping motion. Also, the results in Tab. 5 have been obtained by measuring the friction coefficient in rolling mode and its calculation using Eq. (4). The results show that Eq. (4) is reliable enough to calculate the friction coefficient during the experiments.

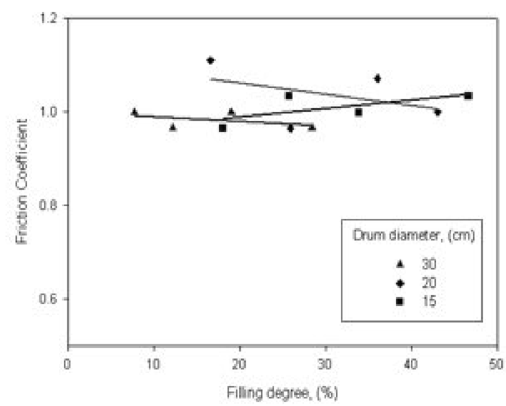

Fig. 8: Effects of filling degree on friction coefficient of rice grains for cylinders with diameters equal to 15, 20, and 30 cm.

Tab. 2: Dynamic angle of repose obtained by three different methods.

Method	Average calculated θ (Eq. 5), (°)	Average measured θ (°)
Rotating cylinder	44.04	43.91
Piling	29.00	-
Emptying	27.41	-

Tab. 3: Friction coefficient of rice grains using two different methods.

Method	Friction coefficient
Rotating cylinder	0.92
Tilting	0.64

Tab. 4: Dynamic angle of repose in rolling mode for rice grains.

Cylinder diameter (cm)	Filling degree (%)	Measured β (°)	Measured α (°)	Measured θ (°)	Calculated θ (°)
15	18.0	44	43	46	43.5
	25.7	46	43	47	44.5
	33.8	45	43	46	44
	46.6	46	44	47	45
20	16.5	48	46	44	47
	25.9	44	41	45	42.5
	36.0	47	44	44.5	45
	43.0	45	43	45	44
30	7.7	45	42	39	43.5
	12.2	44	40	41	42
	19.0	45	43	43	44
	28.4	44	40	41	42

Tab. 5: Friction coefficient in rolling mode for rice grains and calculated values using Eq. (4).

Cylinder diameter (cm)	Filling degree (%)	Calculated friction coefficient
15	18.0	0.931804
	25.7	0.931804
	33.8	0.931804
	46.6	0.964937
20	16.5	1.034687
	25.9	0.86865
	36.0	0.964937
	43.0	0.931804
30	7.7	0.899731
	12.2	0.86865
	19.0	0.931804
	28.4	0.838497

Conclusions

Rotating cylinders approach is a fast and reliable method to determine the friction coefficient and angles of repose of grain materials. The transition from one mode to another mode is specified as a function of the cylinder rotation speed and filling degree. The slumping-rolling transition speed depends on the cylinder diameter and filling degree in the range of 5.0 to 7.9 and 2 to 6.34 rpm, respectively. The effects of rotational speed on α and β for rice grains were significant. With increasing cylinder diameter, the differences in between α and β for rice grains increased ranging from 1 to 4°. Cylinder diameter and filling degree had significant effects on friction coefficient. In this study, it was possible to simultaneously determine the α, β, and friction coefficient of rice grains. Simultaneous determinations of these properties are important in fast and cost-effective studies to model grains' motions in rotary dryers, mixers and silos.

The results of this research can be used in agricultural machines such as combine harvesters, food industry machines, and all equipment related to granular materials. For an estimate of auger friction force, rotating cylinders is a fast and reliable method to determine the friction coefficient and angle of repose of grain materials. Based on the results of this research, cylinder diameter and filling degree had significant effects on the friction coefficient. The effect of rotational speed on the lower angle of repose (α) and upper angle of repose (β) of grains were significant.

Conflict of interest

No potential conflict of interest was reported by the authors.

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