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New method for simultaneously measuring the angles of repose and frictional properties of wheat grains**

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A b s t r a c t. A new method was used for simultaneously measuring the angle of repose and friction coefficient of wheat grains. The method was based on the motion of the grains in a partially-filled horizontal rotating drum at the slumping and rolling modes of motion. Using this method it was also possible to determine two new physical parameters of wheat grains namely: lower angle of repose and upper angle of repose. The suitability of the new method was evaluated with the traditional methods. Measurement method had no significant effect (p = 0.01) on friction coefficient of wheat grains. The mean values of dynamic angle of repose of wheat grains obtained with the emptying and rotating drum methods had no significant difference (p= 0.01). With increasing the filling degree, the lower, upper, and dynamic angle of repose of wheat grains were increased. Rotation speed had no significant effect on upper and dynamic angle of repose. The differences between the lower and upper angle of repose lie in a small range of 1.34-7.65^{o}, depending on the filling degree and rotation speed. The results confirmed that rotating drum method at filling degree of 0.222 and rotation speed of 3 r.p.m. can be used for simultaneously measuring the dynamic angle of repose and friction coefficient of wheat grains. The maximum difference between slumping and rolling dynamic angle of repose was less than 4.5% which implies that lower and upper angle of repose could be used adequately to estimate the dynamic angle of repose of wheat grains.

K e y w o r d s: angle of repose, rotating drum, slumping, rolling, wheat grain

INTRODUCTION

Knowledge of physical properties of grains such as angle of repose (AR), angle of internal friction, and the grain to wall friction coefficient are important to design the handling systems, storage constructions, mixtures, dryers, and milling systems (Spurling *et al*., 2000). The AR is the angle that the surface of an unconstrained pile of grains makes with the horizontal plane (Kingsly *et al*., 2006). The AR is a good indicator of the flow ability of uncompacted materials (Frączek *et al*., 2007; Zou and Brusewitz, 2002).

A variety of traditional methods are currently used to measure the AR of food and agricultural products, namely: pouring, submerging, emptying, and fixed funnel (piling) (Baryeh and Mangope, 2002; Frączek *et al*., 2007; Koocheki *et al*., 2007; Tabatabaeefar, 2003). The latter two are the most commonly used.

In the piling method, grains flow through a funnel slowly onto a surface from a predetermined height for the heap formation (Frączek *et al*., 2007). The AR is equal to the slope of the pile, φ_d, that is determined from the diameter and height of naturally formed heap using the following equation (Kingsly *et al*., 2006; Koocheki *et al*., 2007):

$$\varphi_d = \tan^{-1}\left(\frac{2H}{D_h}\right), \qquad (1)$$

where: H – height of the heap, D_h – diameter of heap (m).

Emptying method is conducted by using a box having a removable front panel. The box is filled with the grains, and the front panel is quickly removed, allowing the grains to flow to their natural slope (Baryeh and Mangope, 2002). The AR is calculated from measurements of the depth and extent of the free surface of the grains in the box (Baryeh and Mangope, 2002).

The traditional method of measuring the friction coefficient of agricultural products is by using an apparatus consisted of a topless and bottomless box and a tilting table with changeable surface (Karimi *et al*., 2009; Tabatabaeefar, 2003). The box is filled with the grains and placed on the adjustable tilting table such that the box does not touch the table surface. The tilting surface is raised gradually until the box with grains just starts to slide down. The angle of the surface is

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read from a scale and the static coefficient of friction is taken as the tangent of this angle (Fathollahzadeh *et al*., 2008; Karimi *et al*., 2009; Tabatabaeefar, 2003).

It is important to researchers to find a method for simultaneously measuring the angles of repose and frictional properties of grains and seeds. In this paper, a new method based on the motion of grains in a horizontal rotating drum (RD) was used for simultaneously measuring the dynamic AR, static AR, and coefficient of friction of agricultural products as well as two new term of AR namely lower and upper AR.

In this new method, the drum is partially filled with grains and is rotated along its axis (Fig. 1). The grains are lifted as a rigid body by the RD wall until they reach a desired angle at which the grains on the bed surface may begin to slide down. The motion behaviour of grains in RD in the transverse plane (perpendicular to the drum axis) can be characterized as one of several possible behaviours namely: slipping, cascading, and cataracting (Mellmann, 2001; Sherritt *et al*., 2003). The regimes of bed motion depend on some parameters such as: grains size and shape, wall friction coefficient, angle of repose of the bed, drum filling degree, and rotation speed (Mellmann, 2001).

Although six modes of motion have been observed in RD, industrial-scale drums are often operated in the rolling or slumping mode (Liu *et al*., 2005a,b; 2006; Sherritt *et al.*, 2003). At the slumping and rolling modes, the slope of the surface of the grains bed was assumed to give the static AR, dynamic AR, upper AR, lower AR, and frictional properties of the grains.

In recent years, many scientists have worked on determining the static and dynamic AR as well as frictional properties of grains and seeds by using the traditional methods. However, it was found no published information on determining the angle of repose and frictional properties of wheat grains by using the RD method. Moreover, numerous publications already exist about measuring the upper and lower AR of engineering materials by using the RD (Liu *et al*, 2005a,b). However, it was found no published paper on lower and upper AR of agricultural products. Therefore the objectives of this study were:

- to investigate the effect of rotation speed, filling degree, and grain moisture content on upper AR, lower AR, static AR, and dynamic AR of wheat grains;
- to determine if the lower and upper AR are independent or dependent on each other;
- to determine the dynamic AR of wheat grains by using the traditional methods of piling and emptying and compare the results with those estimated using the rotating drum method;
- to determine the friction coefficient of wheat grains by using the traditional method of tilting surface and compare the results with those estimated using the rotating drum method.

Horizontal partially filled RD, rotary kilns, are amongst the most well-established unit operations in the processing of granular materials in food and waste industries. They are used to perform the drying of a granular material such as fruits or grains, mixing, cleaning, granulation, size reduction, cooling, separation, and agglomeration (Mellmann *et al*., 2004; Yang *et al*., 2003).

The motion behaviour of granular materials in the transverse plane of a rotary drum depends on the operating conditions (rotational speed and fill degree of drum), the friction of the grains with each other and with the surface of the drum wall, grains size, and grains shape (Cristo *et al*., 2006; Liu *et al*., 2006; Mellmann, 2001; Sherritt *et al*., 2003). The motion behaviour of granular materials in RD is very complicated.

When the drum wall is very smooth slipping motion may be observed. In slipping mode, the grains bed remains at rest and the bed slips at the drum wall. Since no mixing occurs in slipping motion, it is undesired in practice. With higher increase in rotation speed and/or wall friction coefficient the slumping motion can be observed. At this case, the granular bed is lifted as a rigid body by the RD wall until it reaches the upper angle of repose, β at which grains on the bed surface begin to slide down in the form of an avalanche (Fig. 2). During the avalanching, the slope of the bed surface is decreased to the lower AR (α). The bed is then lifted again to the angle β and a new avalanche starts.

At higher rotation speeds, the time interval between the two avalanches in the slumping mode becomes shorter and the slope of the bed surface, Θ, remains approximately

Basic form	Slipping motion		Cascading motion			Cataracting motion	
Subtype	Sliding	Surging	Slumping	Rolling	Cascading	Cataracting	Centrifuging
Schematic							

Increasing the drum velocity

Fig. 1. Possible forms of transverse motion of grains in partially-filled, horizontal rotating drums.

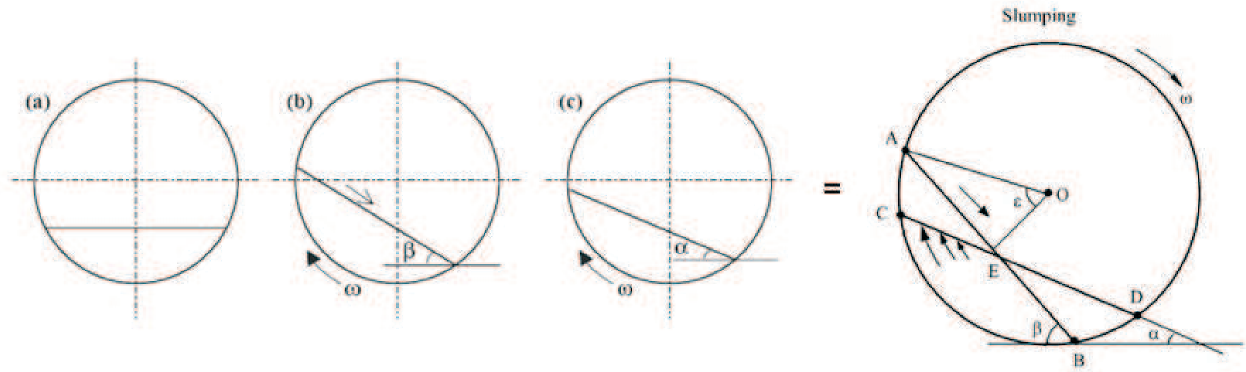


Fig. 2. The slumping mode of motion in the rotating drums.

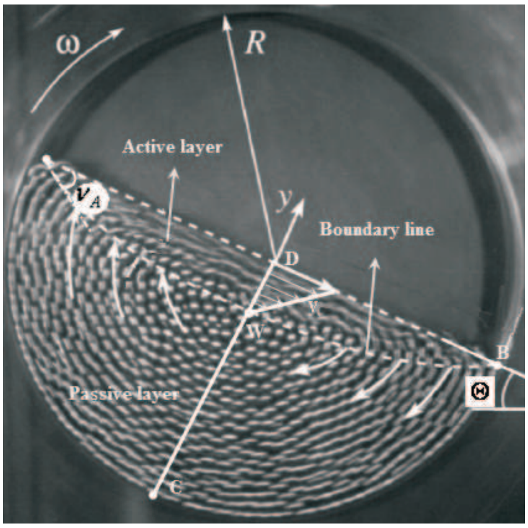


Fig. 3. The parameters of the granular bed in the rolling mode of motion.

constant (Figs 1 and 3). At the rolling mode, the bed is characterized by two layers: a thin active layer (cascading layer or shear layer) and a thick passive layer as discussed in detail by Liu *et al*. (2006) and Mellmann *et al*. (2004).

A further increase in the rotational speed will promote a new transition of flow regimes from a rolling to cascading. As the rotation speed is increased the particles in the upper corner of the rolling bed are lifted higher before detaching from the cylinder wall. The height of the arch of the kidney-shaped bed increases with increasing rotational speed. In the high rotational speed, centrifugal forces become increasingly important in the motion of particles along the bed surface. At this case, the curvature of the cascading surface becomes highly pronounced and particles are projected into the gas space from the upper corner of the bed. In the case of further increases of the rotational speed, particles on the outer paths begin to adhere to the wall and the extreme case of cataracting motion, centrifuging, occurs.

According to Aranson and Tsimring (2006) and Mellmann (2001), the upper AR in the slumping mode is characterized to be equal to static AR. Moreover, the friction coefficient, μ_w, between the grains and the drum surface is assumed to be correlated to the lower AR, α, in the slumping mode (Liu *et al*., 2006; Mellmann, 2001):

$$\mu_w = \tan\alpha\,, \tag{2}$$

Liu *et al*. (2005a,b), Mellmann (2001), and Spurling *et al*. (2000) reported that the slope, Θ, of the grains bed in rolling mode is assumed to be equal to the dynamic AR of the grains. They have also concluded that the average upper and lower AR for the slumping mode is close to the dynamic AR for the rolling mode:

$$\text{Dynamic AR} = \Theta = \frac{\alpha+\beta}{2}\,, \tag{3}$$

where: Θ – slope of the bed surface at the rolling mode (degree), α – lower AR (degree), and β – upper AR at the slumping mode (degree).

According to Liu *et al.* (2006) and Mellmann *et al.* (2004) the inclination angle, υ_A, in the rolling mode (Fig. 3) may be determined from the following equation:

$$\upsilon_A = 0.32\,\Theta(1+f) + 1800 Fr\sqrt{\frac{d}{D}}\,, \tag{4}$$

where: Fr – Froude number; d – grain diameter (m); D – drum diameter (m); f – filling degree – $f = \frac{1}{\pi}(\varepsilon - \sin\varepsilon\cos\varepsilon)$, ε – filling angle acc. to Fig. 2). Based on the Eq. (4), Liu *et al.* (2006) reported that the internal friction coefficient, μ_{if}, of grains along the boun- dary line may be determined by using the following equation:

$$\mu_{if} = \frac{\tan\upsilon_A + \tan\Theta}{1 - \tan(\upsilon)\tan(\Theta)}\,. \tag{5}$$

The various types of bed motion, for example in drum dryers, exhibit significant difference in their mixing behaviour which has also a significant effect on heat transfer rate. The most desirable bed motions for many industrial operations are the slumping and rolling modes, as they helps in promoting good mixing of the particles along with rapid renewal of the exposed material. Thus, characterization of the motion behaviour of a particulate material can be an important consideration in the design and scale-up of RD systems.

Efforts have been devoted to develop mathematical models to predict the transitions between the different types of motion behaviour in rotary drums (Liu *et al*., 2005b; Mellmann, 2001; Sherritt *et al*., 2003). These mathematical models are almost as a function of upper and lower AR, drum diameter, filling degree, rotation speed, and grains size.

MATERIALS AND METHODS

Wheat grains used in this study was obtained from a local market in Tehran, Iran. The grains were cleaned manually to remove all foreign material and broken grains. The initial moisture content of the grains was found to be about 7.5% (w.b.). The samples of higher moisture content were prepared by adding distilled water as calculated using the equation reported by Kingsly *et al*. (2006). The prepared samples were held in polyethylene bags and stored at 5°C in a refrigerator for 48 h before using them for the experiments.

The physical dimensions of the wheat 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; Baryeh and Mangope (2002). The bulk density, true density, porosity and 1000 grain mass were also determined according to the methods proposed by Kingsly *et al*. (2006).

The experimental apparatus used for simultaneously measuring the angles of repose and friction coefficient of wheat grains is shown in Fig. 4. The experimental apparatus was essentially the same as that described by Liu *et al.* (2005a,b). It consisted of a horizontal Teflon drum of length 15 cm and inner diameter of 19 cm. The cylinder was driven by an electric motor with speed control by means of an Inverter. The end of the drum was fixed with a transparent glass plate for visual observation of the cross section of the grains bed.

A digital Canon-PC1210 video camera with 10 Mega-pixel resolutions was used to record the motion of the grains bed into the drum. The camera was placed in such a way that the centre of the camera lens points exactly to the centre of the RD. The films were converted to images with 0.01 s intervals by using the Microsoft Windows movie maker software. An appropriate algorithm was developed in the Image analysis toolbox of the Matlab software (The MathWorks Inc., Natick, MA, USA) to determine the dynamic AR, upper and lower AR by fitting a straight line to the surface of the grains bed.

Fig. 4. Apparatus used for conducting the tests.

The inner wall of the drum was lined with sandpaper of mean particle size of 100 μm as reported by Ingram *et al.* (2005) and Spurling (2000). The sandpaper is used to prevent slipping between the bed of grains and the wall (Li, 2005; Liu *et al*., 2005a; Thalberg *et al*., 2004). At the first some tests were conducted to determine the modes of motion of wheat grains at different filling degree and rotation speed. The term filling degree is equal to portion of the cylinder cross-section occupied by the grains and is correlated to filling angle, ε (Fig. 2), (Ingram *et al*., 2005; Liu *et al*., 2006; Mellmann, 2001). Moreover, a characteristic criterion for the motion of grains in rotary drums is the Froude number, *Fr,* as the ratio of centrifugal force to gravity and calculated as follow (Mellmann, 2001):

$$Fr = \omega^2 R / g = \left(\frac{\pi n}{30}\right)^2 \frac{R}{g}, \tag{6}$$

where: ω – angular velocity (rad s^{-1}), n – rotation velocity (r.p.m.), R – drum radius (m), g – gravitational acceleration (m s^{-2}).

After determining the motion behaviour of wheat grains in RD, the following three sets of tests were conducted to determine the AR and friction coefficient of wheat grains. In the first set of the tests, the effects of filling degree (0.222, 0.285, 0.35, 0.385, and 0.445) and rotation speed (1, 1.5, 2, 2.5, and 3 r.p.m.) were studied on upper and lower AR. In this range of rotation speeds and filling degrees, the grains bed was in the slumping mode. The experiments were replicated five times. For each test, the upper and lower AR were determined by analyzing the recorded films. The dynamic AR of wheat grains was also calculated by using the Eq. (3). The tests were conducted on grains with moisture content of 7.5% (w.b.). Moreover, for each test the friction coefficient between the wheat grains and the drum surface (lined with sandpaper) was calculated using the Eq. (2).

In the second set of the tests, the grain bed was set in the slumping mode of motion (rotation speed of 1 r.p.m.) and the effect of grains moisture content (7.5, 10, 15, and 19% w.b.) was studied on upper and lower AR. Tests were conducted at a constant filling degree of 0.222. For each test, the upper and lower AR were determined. The dynamic AR of wheat grains was also calculated by using the Eq. (3). Moreover, for each test the friction coefficient between the wheat grains and the drum surface was also estimated using the Eq. (2).

In the third set of experiments, the dynamic AR of wheat grains was determined at the rolling mode of motion. The effect of filling degree at 0.222, 0.285, 0.35, 0.385, and 0.445 was studied. A constant speed of 16 r.p.m. where the rolling motion occurred was used. The tests were conducted on grains with moisture content of 7.5% (w.b.). For each test and using the recorded images, the constant slope Θ (dynamic AR) of the grains bed was determined (Fig. 3).

In this study, validation of RD method for measuring the AR of wheat grains was evaluated by comparing the results with those obtained by traditional methods of emptying and piling. The emptying AR was determined by using a fiber-glass box of 25 x 25 x 20 cm, having a removable front panel (Koocheki *et al.*, 2007). The piling AR determined by pouring the grains through a fixed funnel (1 cm in diameter) slowly onto a surface from a predetermined height of 15 cm for the heap formation (Frączek *et al.*, 2007).

The effect of moisture contents (7.5, 10, 15, and 19% w.b.) was studied on dynamic AR. For each test, average value of six replications was reported. The AR data were individually subjected to variance analysis and the difference between the means was determined by Duncan test.

Validation of the RD method for measuring the AR of wheat grains was evaluated by comparing the AR values with those obtained by emptying and/or piling method as follow:

$$\text{Relative difference} = R_{Ad} = \frac{\text{AR}_D - \text{AR}_T}{\text{AR}_D}, \tag{7}$$

where: AR_D – angle of repose measured using the rotating drum method (degree), and AR_T – angle of repose measured using the emptying and/or piling method (degree).

The suitability of the RD method for measuring the friction coefficient between the wheat grains and the drum surface was evaluated with the traditional method of inclined surface as carried out by Karimi *et al.* (2009); Koocheki *et al.* (2007) and Tabatabaeefar (2003).

As mentioned before, the inner wall of the rotating drum was lined with sandpaper to prevent slipping between the bed of grains and the drum wall. Therefore, friction coefficient experiments of wheat grains in the moisture range of 7.5 to 19% (w.b.) were conducted on steel sheets covered with sandpaper of mean particle size of 100 μm.

For each test, a fibreglass box measuring 80 mm in length and 50 mm in diameter opened at both ends was filled with the grains and placed on the adjustable tilting surface of the apparatus such that the box did not touch the surface. The tilting surface was then raised gradually by an electric motor and transmission system until the cylinder with grains just started to slide down. The inclination angle of the tilting surface was read from a graduated scale and the static friction coefficient was calculated. The experiments were replicated six times. The comparative evolution of the RD and inclined surface methods for measuring the friction coefficients of wheat grains was characterized by relative difference as follow:

$$\text{Relative difference} = R_{Fd} = \frac{fc_D - fc_1}{fc_D}, \tag{8}$$

where: fc_D – friction coefficient measured using the RD method, and fc_1 – friction coefficient measured using the inclined surface method.

Table 1. Dimensional properties of the wheat grains

Parameter	Mean	SD
Length (mm)	6.87	0.40
Width (mm)	3.43	0.29
Thickness (mm)	2.80	0.24
Geometric mean diameter (mm)	4.03	0.23
Sphericity	0.59	0.03
1000-grain mass (g)	46.48	1.34
Surface area (mm^2)	43.17	4.67
Volume of a single grain (mm^3)	22.41	3.82
Bulk density (g cm^{-3})	0.77	0.01
True density (g cm^{-3})	1.27	0.028
Porosity (%)	38.97	1.66

RESULTS AND DISCUSSION

The angle of repose and transverse motion behaviour of grains in rotating drums are strongly depended on grains physical properties such as density, size, and shape (Zhou *et al.*, 2002). The grain size also affects the slumping frequency of the bed (Mellmann, 2001). The transition to cascading mode of motion is also dependent on grain size (Mellmann, 2001).

The mean and standard deviation of the dimensional properties of the wheat grains used in this study are summarized in Table 1. The length of the grains ranged from 5.78 to 7.72 mm, width ranged from 2.41 to 4.02 mm, and thickness ranged from 1.97 to 3.4 mm. The geometric mean diameter of the grains ranged from 3.14 to 4.55 mm while the sphericity ranged from 0.51 to 0.66. The wheat grains had a true density of 1.22-1.28 g cm^{-3}. The results obtained in this study were in general agreement with those reported by Al-Mahasneh and Rababah (2007), and Tabatabaeefar (2003).

The results of size distribution data showed that 84% of the grains had a length ranged between 6.45 and 7.35 mm, 82% of width ranged between 3.25 and 3.75 mm, and 83% of thickness ranged between 2.6 and 3.0 mm. Moreover, about 83% of the grains had a geometric mean diameter ranging from 3.9 to 4.3 mm. For the design of rotary kiln installations, an estimation of the grains size distribution is necessary. According to Mellmann (2001), for grains with a very broad size distribution, segregation can appear.

The experimental data showed that the slumping mode of motion was occurred in rotation speeds of 0.5 to 11 r.p.m. ($Fr = 2.65\ 10^{-5}$ - $1.28\ 10^{-2}$) depending on filling degree. For filling degrees higher than 0.285, the slumping mode took place at rotation speeds of 0.5 to 5 r.p.m. ($Fr = 2.65\ 10^{-5}$ - $2.65\ 10^{-3}$), whereas for the lower filling degrees, the slumping mode was occurred at rotation speeds of 5 to 11 r.p.m. ($Fr = 2.65\ 10^{-3}$ - $1.28\ 10^{-2}$).

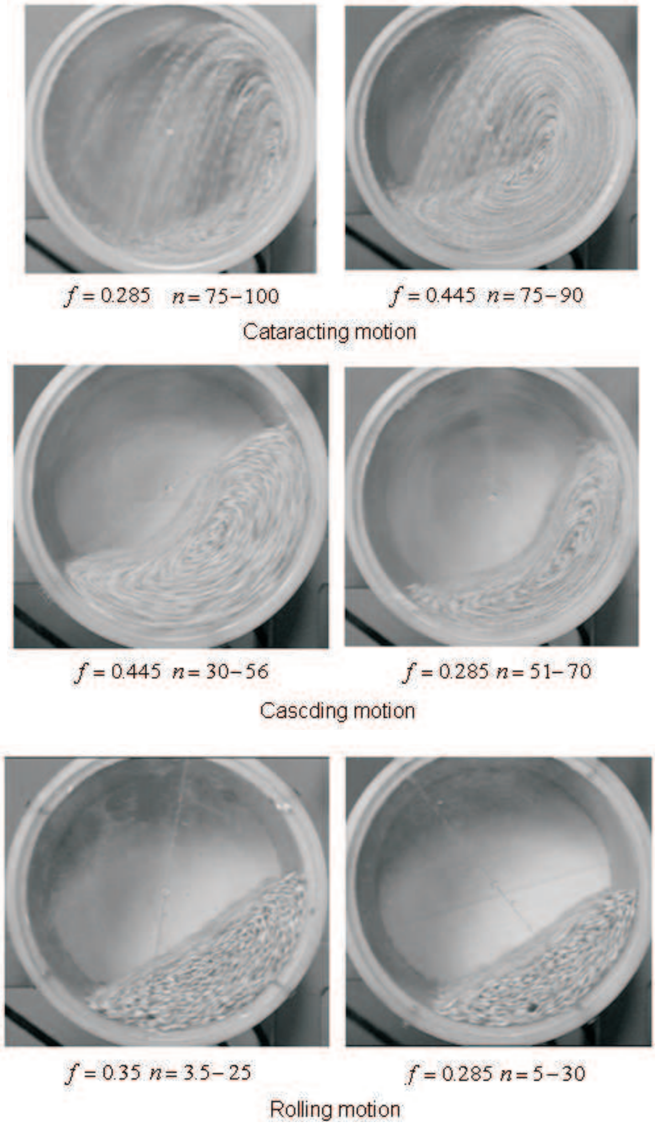


Fig. 5. Typical pictures of motion behaviour of wheat grains in the RD at different filling degrees and rotation speed.

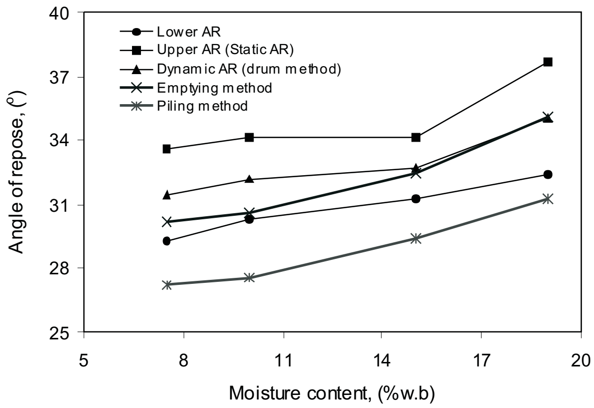


Fig. 6. Effect of moisture content on lower, upper, and calculated dynamic AR of wheat grains (filling degree = 0.222, rotation speed = 1 r.p.m.).

Analysis of the data also showed that the rolling mode was occurred at rotation speeds of 5 to 60 r.p.m. (Fr = 2.65 10^{-3} - 0.38) depending on filling degree. Cristo *et al.* (2006) have also reported similar results for coffee beans. Figure 5 shows some typical pictures of motion behaviour of wheat grains in the RD at different filling degrees and rotation speed.

Cristo *et al.* (2006) and Liu *et al.* (2005b) have also reported similar results for the effect of filling degree on the transition from slumping to rolling for coffee beans, gravel, limestone, and sand. Henein *et al.* (1983) found that for a range of materials, the bed was operating in the rolling regime at Froude numbers above 10^{-3} even at their lowest filling degree of 0.40. Mellmann (2001) also showed that rolling beds typically occur at Froude numbers between 10^{-4} and 10^{-2} with a filling degree of greater than 0.10. Dury *et al.* (1998) found that for mustard seeds (d = 2.5 mm) there was a transition from slumping to rolling around Fr = 1.2 10^{-3} when drum diameter was 69 mm and filling degree was 0.5.

The effects of moisture content on lower and upper AR of wheat grains measured in slumping mode of motion are illustrated in Fig. 6. It should be noted that these results are referred to a filling degree of 0.222 and rotation speed of 1 r.p.m. The results showed that moisture content had significant (p = 0.01) increasing effect on upper AR (static AR) and lower AR of wheat grains (Fig. 6). The lower and upper *AR* were found to increase linearly from 29.3 to 32.4 and 33.6 to 37.7°, respectively in the moisture range of 7.5 to 19% w.b. (Fig. 6). This response indicates that the flowability of the grains was reduced at higher moisture contents. Moisture content affects the AR of wheat grains because of greater friction forces among the grains (internal friction). In such a case, grains may more easily jam and form 'aggregates'.

Figure 5 also shows the comparison between the dynamic AR of wheat grains at different moisture content and for three different measurement methods, rotating drum and two traditional methods of emptying and piling. The

T a b l e 2. Result of variance analysis for the effect of measurement method and moisture content on dynamic AR of wheat grains

Source	*df*	Mean square error	F value
Treatment	11	16.03	7.33*
Method (Me)	2	42.73	19.54*
Moisture content (Mc)	3	28.34	12.96*
Me x Mc	6	0.98	0.45 ns
Error	24	2.18	

*significant at p=0.01, ns – no significant.

T a b l e 3. Duncan multiple range tests for comparison of average dynamic AR of wheat grains for different moisture contents and measurement methods

Parameter	Dynamic AR[a] (°)
Method	
Rotating drum	32.33 A*
Emptying	31.84 A
Piling	28.85 B
Moisture contents	
7.5	29.61 B
10	29.78 B
15	31.17 B
19	33.45 A

*The similar letter have no significant difference at p = 0.01, [a]calculated by using Eq. (3).

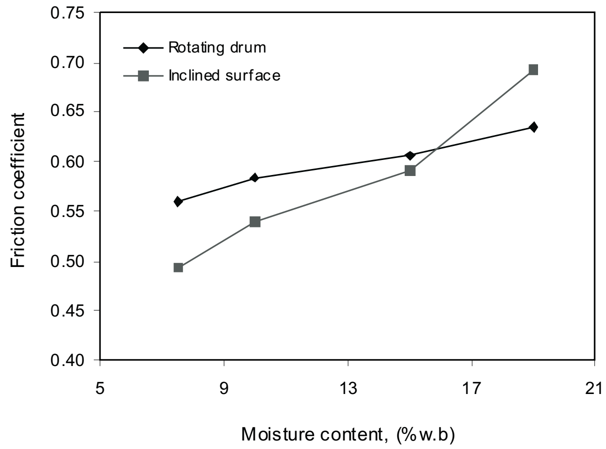


Fig. 7. Effect of moisture content and measurement method on friction coefficient of wheat grains (filling degree = 0.222, rotation speed = 1 r.p.m.).

result of analysis of variance showed that both moisture content and measurement method had significant effect ($p = 0.01$) on dynamic AR of wheat grains (Table 2).

Moisture content had an increasing effect on dynamic AR. However, the difference between the mean values of dynamic AR at moisture contents of 7.5, 10, and 15% was not significant at 1% level (Table 3). With increasing moisture content from 7.5 to 19% w.b, the mean values of emptying, piling, and RD dynamic AR showed an increasing trend from 30.2 to 35.07, 27.2 to 31.27, and 31.45 to 35.04°, respectively (Fig. 6). These results are similar to the observations of other authors (Davies and El-Okene, 2009; Frączek *et al*., 2007; Tabatabaeefar, 2003).

Tabatabaeefar (2003) also found that dynamic AR of wheat grains increased from 37 to 45° in the moisture range of 8 to 22% d.b. The work conducted by Karimi *et al.* (2009) on wheat grains also showed that with increasing moisture content from 8 to 18% w.b., dynamic angle of repose increased from 29.89 to 36.5°. Frączek *et al*. (2007) also concluded that piling AR of nutka wheat grains varied from 25.9 to 35.8° for moisture range of 7.4 to 19.8% w.b.

The results indicated a statistically significant difference ($p = 0.01$) between mean values of piling and RD dynamic AR as well as between emptying and piling dynamic AR. For all level of moisture content considered, the maximum dynamic AR were belonged to RD method (Fig. 6, Table 3). However, the difference between emptying and RD dynamic AR were not significant at 1% level. The relative difference between mean values of emptying and RD dynamic AR ranged between -0.001 to 0.050. Corresponding values for piling and RD dynamic AR ranged between 0.101 and 0.144. With increasing the grain moisture content, the relative difference between the emptying and RD dynamic AR decreased (relative difference of 0.039 at moisture content of 7.5% in comparison with relative difference of -0.001 at moisture content of 19%).

The effects of grains moisture content and measurement method (rotating drum and traditional method of inclined surface) on friction coefficients of wheat grains are illustrated in Fig. 7. The results showed that moisture content had significant effect on friction coefficients of wheat grains ($p = 0.05$), but the effect of measurement method was not significant at 1% significance level.

With increasing the moisture content from 7.5 to 19%, the friction coefficient of wheat grains increased from 0.56 to 0.63 for the rotating drum method and from 0.49 to 0.69 for the inclined surface. However, the results of Duncan's multiple range tests showed that just the difference between mean values of friction coefficients at moisture contents of 7.5 and 19% was significant at 5% significance level. Tabatabaeefar (2003) reported that with increasing moisture content from 8 to 22% d.b., the friction coefficient of wheat grains on plywood, galvanized iron, and stainless steel surfaces increased from 0.375 to 0.450, 0.340 to 0.415, and 0.323 to 0.398, respectively. As expected, the estimated friction coefficient of wheat grains on sheets covered with sandpaper was grater than those reported by Tabatabaeefar (2003) for plywood, galvanized iron, and stainless steel surfaces.

The relative difference between the friction coefficients of wheat grains measured using the rotating drum and inclined surface method ranged from 0.02 to 0.12. In general, these findings confirm that rotating drum method can be used for measuring the friction coefficient of wheat grains with an acceptable range of accuracy.

Here, the results of determining the effect of rotation speed and filling degree (in slumping mode) on lower and upper AR as well as on calculated dynamic AR of wheat grains are reported. It should be noted that these results are referred to moisture content of 7.5% w.b. The mean values of the lower, upper, and calculated dynamic AR were 30.2, 35.2, and 32.7 degrees, respectively. Corresponding values

T a b l e 4. Result of variance analysis for the effect of rotation speed and filling degree on the lower and upper AR of wheat grains

Source	*df*	Mean square error		
		AR		
		Lower	Upper	Dynamic (Eq. (4))
Treatment	24	10.48*	4.80*	6.00*
Drum velocity (V)	4	2.01**	0.099 ns	0.71 ns
Filling degree (f)	4	50.70*	24.50*	33.40*
Vx f	16	2.54*	1.05 ns	0.48 ns
Error	50	0.66	0.75	0.34

**significant at p=0.05. Other explanations as in Table 3.

of standard deviations were 1.96, 1.43, and 1.48, respectively. The low values of standard deviations confirm the accuracy and repeatability of the tests.

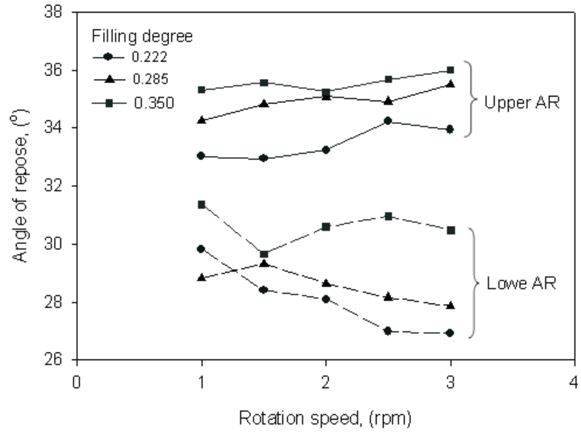
Analysis of variance on the data indicated that filling degrees had significant ($p = 0.01$) effects on upper, lower, and dynamic AR of wheat grains (Table 4). Rotation speed had no significant effect ($p = 0.05$) on upper and dynamic AR, but it was significant for lower AR ($p = 0.05$). Meanwhile, the interaction effects of filling degree and rotation speed was significant ($p = 0.01$) for lower AR.

The results showed that with increasing the filling degree from 0.222 to 0.385, the mean values of lower and upper AR of wheat grains were increased from 28.0 to 31.9 and 33.5 to 36.2°, respectively, but with higher increase in filling degree from 0.385 to 0.445 both the upper and lower AR showed non significant decreasing and/or increasing trends (Fig. 8, Table 5). Liu *et al.* (2005a) found that the effect of the filling degree on upper and lower AR of glass beads was negligibly small.

Steel balls and fertilizer pellets investigated by Liu *et al.* (2006) had also an upper AR of 34.97 and 40.7°, respectively. Henein *et al.* (1983) concluded that the upper AR of all materials they investigated were greater than 32°. It was found no published paper on measuring the upper and lower AR of agricultural product to make comparisons. However, as reported by Liu *et al.* (2005a) it is almost impossible to measure the lower and upper AR with an error lower than 0.5°.

The results showed that with increasing the rotation speed from 1 to 3 r.p.m., the mean values of upper and dynamic AR did not show any clear increasing and/or decreasing trends (Table 5). Experiments from other authors on engineering granular materials have also demonstrated that with increasing rotation speeds, the upper and lower AR keep either constant or they show only a very weak increase and/or decrease (Dury *et al.*, 1998; Henein *et al.*, 1983; Liu *et al.*, 2005a; Mellmann, 2001; Tegzes *et al.*, 2002). Spurling (2000) concluded that in the slumping mode the upper AR was weakly dependent on the rotation speed.

a



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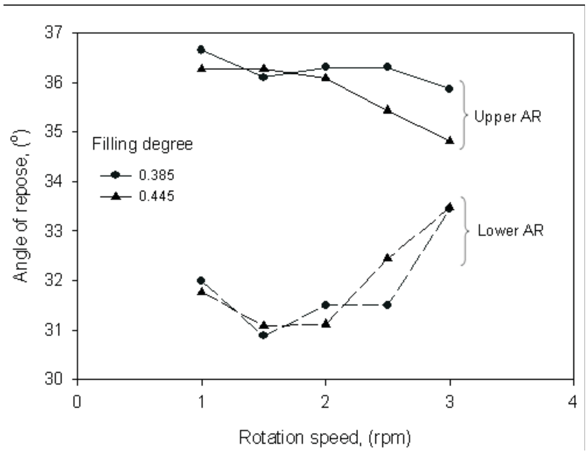

Fig. 8. Effect of rotation speed on upper and lower AR of wheat grains at: a – low and b – high filling degrees.

T a b l e 5. The mean values of upper and lower AR of wheat grains at different rotation speeds and filling degrees

Parameter	AR		
	Upper	Lower	Dynamic[a]
	Filling degree		
0.222	33.5C*	28.0C	30.8 C
0.285	34.9B	28.6C	31.7 C
0.350	35.6AB	30.6B	33.1 B
0.385	36.2A	31.9A	34.1 A
0.445	35.8AB	32.0A	33.9 AB
	Rotation speed (r.p.m.)		
1.0	35.1 A	30.7A	32.9 A
1.5	35.1 A	29.9B	32.5 A
2.0	35.2 A	30.1AB	32.7 A
2.5	35.3 A	30.0 AB	32.7 A
3.0	35.2 A	30.4 AB	32.8 A

*Means with the similar letter have no significant difference at $p = 0.01$, a – calculated by using Eq. 3.

Due to the significant interaction effects between rotation speed and filling degree, the effect of rotation speed on upper and lower AR of wheat grains was not the same at all levels of filling degree. In the low filling degrees of 0.222 to 0.35 (Fig. 8a), the lower AR had a decreasing trend while the upper AR increased with the rotation speed. However, in the high filling degrees of 0.385 to 0.445 (Fig. 8b), the lower AR showed an increasing trend while the upper AR decreased with the rotation speed.

For the wheat grains, the differences measured between the lower and upper AR ($\beta - \alpha$) lies in a small range of 1.34-7.65°, depending on the filling degree and rotating speed. Such a difference might appear quite small, however it is extremely reproducible. Similar results have been reported by Liu e*t al*. (2005a) for some engineering granular materials. Davidson *et al*. (2000) found that the value of ($\beta - \alpha$) for sand (d = 0.4 mm) was in a range from 2 to 4°.

The results of upper and lower AR are useful in practice and in mathematical modeling to predict the critical rotation speeds for transition from slumping to rolling mode of motions of materials (Liu *et al*., 2005b). The experiments results showed that the upper and lower AR of wheat grains depends on each other as shown in Fig. 9. Similar results have been reported by Dury *et al*. (1998) for mustard seeds and Henein *et al*. (1983) for limestone.

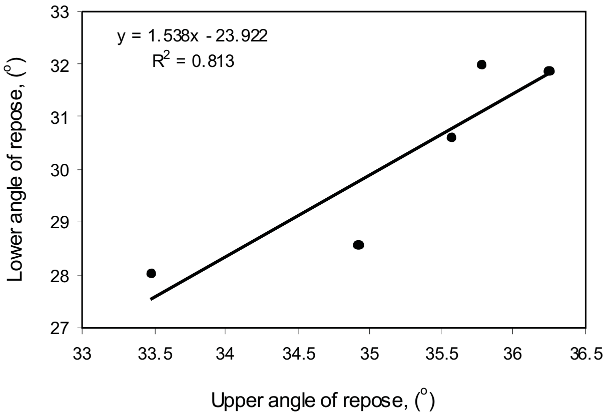

Fig. 9. Correlation between the lower and upper AR of wheat grains measured at 5 different filling degrees.

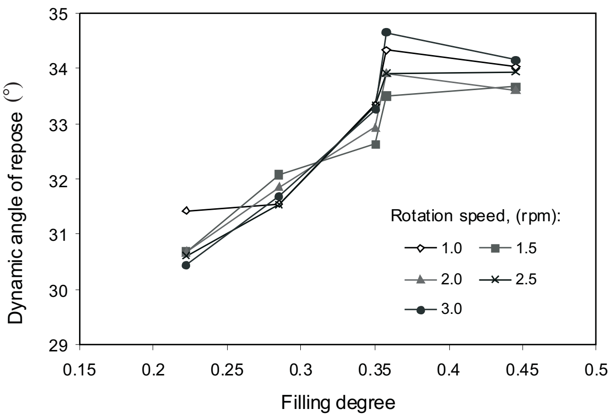

Fig. 10. Effects of filling degree and rotation speed on dynamic AR of wheat grains at 7.5% moisture content.

The results showed that with increasing the filling degree from 0.222 to 0.385, the mean values of dynamic AR of wheat grains were increased from 30.8 to 34.1°, but with higher increase in filling degree from 0.385 to 0.445 non significant decreasing and/or increasing trends were observed (Table 5, Fig. 10). The results also showed that with increasing the rotation speed from 1 to 3 r.p.m., the mean values of calculated dynamic AR did not show any clear increasing and/or decreasing trends.

It was found no published paper on studying the effect of rotation speed and filling degree on dynamic AR of seeds and grains in slumping mode. Experiments from other authors on engineering granular materials have also demonstrated that with increasing rotation speed, the dynamic AR keep either constant or they show only a very weak increase and/or decrease (Dury *et al*., 1998; Henein *et al*., 1983; Liu *et al*., 2005a; Mellmann, 2001; Tegzes *et al*., 2002).

As discussed before, the upper AR (β) is characterized to be equal to static AR (Aranson and Tsimring, 2006; Mellmann, 2001). The results of this study showed that the mean values of dynamic AR of wheat grains at different filling degrees were smaller than the corresponding static AR (Figs 8, 10). Henein *et al*. (1983), Mellmann (2001), Spurling (2000), and Zou and Brusewitz (2002) have also reported similar results for granular engineer materials. Khakhar *et al*. (1997) and Tabatabaeefar (2003) also reported that static AR was larger than dynamic AR determind by using traditional methods.

It was found no published paper on measuring the upper, lower, and dynamic AR of agricultural products using the rotating drum to make comparisons. Here, the results of the comparison among rotating drum, emptying, and piling methods of measuring the dynamic AR of wheat grains have been reported.

The mean values of emptying and piling dynamic AR of wheat grains at 7.5% moisture content were determined to be 30.2 and 27.2°, respectively (Fig. 6). These results are similar to the observations of other authors (Davies and El-Okene, 2009; Frączek *et al*., 2007; Tabatabaeefar, 2003).

The results showed that for all level of rotation speed and filling degree (Fig. 10), the rotating drum method yield higher dynamic AR values than emptying (30.2°) and piling (27.2°) method at 7.5% moisture content. The relative difference between rotating drum and emptying as well as between rotating drum and piling dynamic AR ranged from 0.007 to 0.128 and 0.106 to 0.215, respectively.

It is evident that emptying dynamic AR are more close to those obtained by rotating drum method. Emptying dynamic AR of wheat grains at 7.5% moisture content (30.2°) agree well with the rotating drum data for filling degree of 0.222, but the relative difference starts to become higher when filling degree increased and reaches up to 0.108 at filling degree of 0.445 (Fig. 10). In general, the relative differen- ce between the rotating drum and piling dynamic AR (0.167) was 2.2 times higher than that for rotating drum and emptying dynamic AR (0.075).

The rotation speed did not show any clear increasing or decreasing trend on relative difference between the RD and tilting surface method. It could be concluded from Fig. 10 that for low filling degrees of 0.222 to 0.285, the minimum relative differences belonged to rotation speeds of 2.5 to 3 r.p.m., but at high filling degrees of 0.35 to 0.445, the minimum relative differences belonged to rotation speeds of 1.5 to 2 r.p.m.

The differences among the different measurement methods may be due to the difference in sample mass of grains. Train (1958) also compared four methods-fixed funnel, fixed bed cone, tilting box, and rotating drum to measure the AR of powders. He found that direct comparison between methods was difficult due to differences in sample masses. He also concluded that the first two methods had lower angle of repose than the second two methods. In general, this findings confirmed that rotating drum method, at filling degree of 0.222 and rotation speed of 3 r.p.m., can be used for measuring the dynamic AR of wheat grains with an R_{Ad} of 0.007, which is in the range of acceptance for the agricultural experiments.

The results of this study showed that the estimated values of friction coefficients (Eq. (2)) of wheat grains on drum surface (covered with sandpaper) at 7.5% moisture content ranged from 0.51 to 0.66, depending on filing degree and rotation speed (Table 6). It was found no published paper on measuring the friction coefficients of wheat grains using the rotating drum to make comparisons. Here, the mean values of friction coefficients of wheat grains at 7.5% moisture content measured using the rotating drum method, at different filling degree and rotation speed, compared with those obtained by traditional method of tilting surface (Fig. 6).

The mean value of friction coefficients of wheat grains at 7.5% moisture content measured using the tilting surface method was 0.493 (Fig. 7). Tabatabaeefar (2003) also found that friction coefficients of wheat grains at moisture content of 8% on plywood, galvanized iron, and stainless steel surfaces was 0.375, 0.34, and 0.232, respectively. Karimi *et al*. (2009) reported that friction coefficients of wheat grains at moisture content of 8% on plywood and galvanized iron surfaces was 0.46 and 0.34, respectively.

It can be concluded from Table 6 that for wheat grains at 7.5% moisture content, tilting surface method (0.493) yield less friction coefficient values than rotating drum method, at all level of filling degree and rotation speed. The relative difference between the two methods of measurement ranged between 0.02 and 0.25, depending on filing degree and rotation speed. Table 6 shows that with increasing filling degree, the difference between the two methods of measurement increased. The friction coefficients obtained with the rotating drum at filling degree of 0.222 and rotation speed of 3 r.p.m. agree well with the tilting surface data (R_{Fd} = 0.028), but the relative difference between the two methods increased when filling degree increased.

The rotation speed did not show any clear increasing or decreasing trend on relative difference between the RD and tilting surface method. As it could be concluded from Table 6, for low filling degrees of 0.222 to 0.285, the minimum relative differences were observed for rotation speed of 3 r.p.m., but at high filling degrees of 0.35 to 0.445, the minimum relative differences were observed for rotation speed of 1.5 r.p.m. In general, these findings confirmed that rotating drum method, at filling degree of 0.222 and rotation speed of 3 r.p.m., can be used for simultaneously measuring the dynamic AR with R_{Ad} of 0.007 and friction coefficient of wheat grains with R_{Fd} of 0.028.

The effects of filling degree on the dynamic AR (Θ) of wheat grains measured in the rolling mode of motion is illustrated in Fig. 11. With an increase in filling degrees from 0.222 to 0.445, the mean values of rolling dynamic AR increased from 31.81 to 33.97°. The results showed that for each filling degree, the rolling dynamic AR were close to the corresponding calculated slumping dynamic AR. The relative difference between rolling and slumping dynamic AR

T a b l e 6. Friction coefficients of wheat grains as affected by filling degree and rotation speed (at 7.5% moisture content)

Rotation speed (r.p.m.)	Filling degree[a]				
	0.222	0.285	0.350	0.358	0.445
1.0	0.57	0.55	0.61	0.62	0.62
1.5	0.54	0.56	0.57	0.60	0.60
2.0	0.53	0.55	0.59	0.61	0.60
2.5	0.51	0.53	0.60	0.61	0.64
3.0	0.51	0.53	0.59	0.66	0.66

[a]Friction coefficient of wheat grains at 7.5% moisture content measured using the tilting surface method was 0.493.

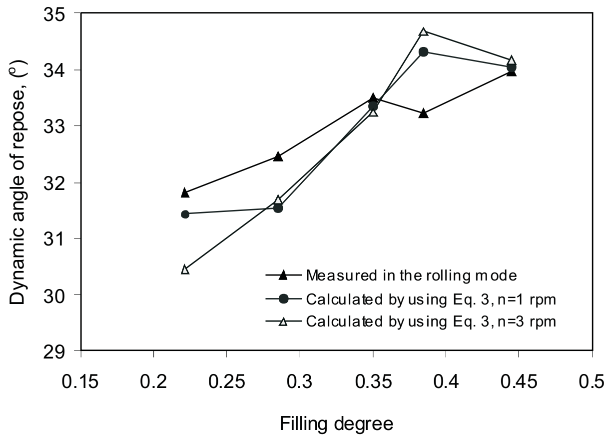

Fig. 11. Dynamic AR of wheat grains measured in the rolling mode and its slumping calculated values (Eq. (3)) at two different rotation speeds.

ranged from 0.001 to 0.045. According to Figs 6 and 11, the minimum and maximum relative differences between slumping and rolling dynamic AR were observed at rotation speed of 1 and 3 r.p.m., respectively. Figure 11 plots the comparison of slumping dynamic AR of wheat grains at rotation speeds of 1 and 3 r.p.m. and rolling dynamic AR as a function of filling degree. Both rolling and slumping dynamic AR increased progressively with the filling degree. The maximum difference between slumping and rolling dynamic AR was less than 0.045 which implies that Eq. (3) could be used adequately to estimate the dynamic AR of wheat grains.

CONCLUSIONS

1. The new introduced method for measuring simultaneously the dynamic and static angles of repose as well as friction coefficient of wheat grains was fast and reliable. Using this method it was also possible to determine two new physical parameters of wheat grains namely: lower and upper angles of repose.

2. Moisture content had significant ($p = 0.01$) increasing effect on dynamic, upper, and lower angle of repose of wheat grains. Moisture content had also an increasing effect on dynamic angle of repose of wheat grains measured using the traditional methods of piling and emptying. For all levels of moisture content considered, the rotating drum method yields higher values of dynamic angle of repose compared to the piling and emptying methods. However, the difference between emptying and rotating drum dynamic angle of repose were not significant.

3. Moisture content had a significant increasing effect on the friction coefficient of wheat grains measured by the rotating drum and inclined surface methods. However, measurement method had no significant effect ($p = 0.01$) on friction coefficient of wheat grains.

4. Filling degree in the range of 0.222 to 0.385, had an increasing effect on lower, upper, and dynamic angle of repose of wheat grains. Rotation speed, in the range of 1 to 3.5 r.p.m., had no significant effect on upper and dynamic angle of repose.

5. The results confirmed that rotating drum method at filling degree of 0.222 and rotation speed of 3 r.p.m. can be used for simultaneously measuring the dynamic angle of repose and friction coefficient of wheat grains.

6. The results showed that dynamic angle of repose measured in the rolling mode were close to the corresponding values calculated using the lower and upper angle of repose in the slumping mode.

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