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Effect of Moisture Content on Frictional Properties of Some Selected Grains in Indonesia

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ABSTRACT

The frictional property of grains is one of the most important engineering parameters in developing solid bulk handling of grains. It is necessary for designing agricultural facilities and production process activities. These properties are expressed as internal friction angle (φ) and wall friction angle (θ), which are known to be affected by the moisture content of the grains. This research investigates the effect of moisture content on the values of φ and θ of some selected grains. In the research, some indigenous Indonesian grain types, including rough rice, white rice, corn, soybean, and coffee, each in three varieties and three level of moisture contents, were used as the research samples. Those angles were measured using a self-constructed direct shear cell apparatus. Three different normal loads for each grain type were used with three replications. It is concluded that φ and θ of the tested grains increase with moisture contents with different trends of increments. The relationship of those angles with moisture contents can be expressed as linear regression equations. The slope of the regression lines for both φ and θ is significantly affected by grain type ($p<0.05$). For φ, coffee (*Excelsa*) is the most susceptible to the change in moisture content, while dent corn (*Hibrida*) is the least affected one. For θ, soybean (*Galunggung*) is the most susceptible to the change in moisture content, while rough rice (*Mapan 5*) is the least affected one.

Keywords: Direct shear cell, grain, moisture content, φ, θ

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INTRODUCTION

Indonesia is an agricultural country located in the tropics. Therefore, the climate conditions in Indonesia support the cultivation of perennial plants and annual crops all year round. It causes abundant agricultural products yearly in Indonesia, especially for grains such as rough rice, white rice, corn, soybean, and coffee. Various data sources have shown that the production of rough rice in Indonesia reaches 55,269,619.39 tons, white rice reaches 31,627,132 tons (BPS-Statistics Indonesia, 2021), corn 11,800,000 metric tons, soybean 480,000 metric tons (USDA, 2022), and coffee 726,000 tons (ICO, 2021). Indonesia is the third country with the largest paddy rice production (USDA, 2022) and the fourth country with the world's largest coffee export (ICO, 2021). This illustration may give an idea of how high grain production in Indonesia is yearly. However, high-grain productions are still handled manually in post-harvest activities. Harvesting is mostly done manually, transportation and storage are done using a sack while drying, cleaning, and other activities are still handled manually. This handling method has many drawbacks, such as high grain losses, high labor demand, high cost of production, slow handling activity, and finally results in inefficient post-harvest handling practices.

Presently, most post-harvest handling of cereal grains, especially maize, and sorghum, are done manually in Nigeria and other developing countries (Okolo et al., 2020). It is reported that in developing countries, crop harvesting activity is mainly conducted manually. Meanwhile, in developed countries, almost all crops are harvested using a combined harvester. It is reported that around one-third of the produced food is lost. This loss may occur during harvest and post-harvest periods due to problems in processing, handling, packing, transportation, and retail. One of the underlying causes of food losses is inadequate infrastructure (Vagsholm et al., 2020). It is common for many developing countries to have overall post-harvest losses of cereals and legumes reaching 10 to 15% (FAO, 2021). If it is related to the large grain production in Indonesia, the loss of grains will reach millions of tons yearly. The new postharvest handling methods should be investigated to save grain production in Indonesia.

Developed countries started handling grains mechanically in bulk long ago, and this method has been revealed to give very efficient postharvest handling in the grain production system. Material handling is moving and storing materials at the lowest possible cost using proper methods and equipment. Material handling is a very important step since this will handle the material properly, keep it from damage, and deliver it safely to the destination with the desired quality and conditions. Adequate material handling will give efficient handling and avoid accidents during the process (Alghalayini, 2020). In bulk grain handling, the grain is handled mechanically using various machines, from harvesting to storage. This method of handling is capable of handling very large grain volumes in every activity with minimum losses. Losses during the post-harvest period in developed countries are lower than in developing countries due to more efficient farming systems, better transportation services, and other supported facilities (Pawlak & Kołodziejczak, 2020; Nicastro & Carillo, 2021). This high agricultural production needs to be handled quickly and efficiently to avoid high losses during postharvest.

In order to improve post-harvest grain handling in Indonesia, there is a need to change the method of grain handling from traditional and manual handling to modern mechanical bulk handling practices. Improvements in material handling have positively affected workers more than any other area of work design and ergonomics. Further, it is stated that the equipment for material handling has reduced the boredom of work. It reduces production costs and improves work-life quality for almost everyone in the modern industry (Stephens & Meyers, 2013). Developing and improving the machine in the agricultural area, commonly known as mechanization, can also overcome aging rural labor (Liu et al., 2021). It is also mentioned that mechanizing the post-harvest handling process using various equipment will add value to the process and product and minimize handling time (Okolo et al., 2020). However, problems arise in changing the handling method, such as the unavailability of research facilities and lack of data sources. Activities correlating to developing and promoting bulk grain handling are still very limited. Many challenges need to be solved, and it should start by increasing research activities related to bulk grain handling. In modern bulk grain handling, it is necessary to design the process, equipment, and machines to handle the grains scientifically.

This design process needs some information when dealing with grain properties. In general, the engineering properties of grains are very important for designing the basic parameters required for drying, storage, and equipment, particularly for their handling, processing, and storage (Bako & Bardey, 2020). This similar statement is also reported in various research works (Rodrigues et al., 2019; Wang & Wang, 2019; Fayed et al., 2020; Kaliniewicz et al., 2020; Etim et al., 2021; Kruszelnicka, 2021; Fadeyibi et al., 2021; Gierz et al., 2022).

One of the parameters needed to develop modern bulk grain handling is the friction properties of the grain, which are the internal friction angle (φ) and the wall friction angle (θ). φ is a quantification expressed in the angle value of the friction between the grain on itself, while θ is the angle formed when the grain slides on the surface of the wall material. These two parameters can be determined using direct shear cell apparatus. These values are needed in designing silos, hoppers, some conveyor types, and others. Parameters of φ and θ are among the basic parameters of bulk materials (Vagová et al., 2019). Knowledge of the frictional properties of plant materials is essential in designing mechanical units of machines and selecting parameters for many post-harvesting processes (Wójcik et al., 2020; Tang et al., 2021; Shi et al., 2022). A similar expression of the importance of frictional properties of the grain for machinery or facilities design is also pointed out by many other researchers (Wang & Wang, 2019; Li et al., 2020; Kopeć-Jarosz & Wójcik, 2021).

Frictional properties of agricultural grains are often measured using a direct shear cell. The direct shear test is widely used to determine frictional properties of agricultural materials for various purposes, such as designing storage structures, processing equipment, and machinery (Zeng & Wang, 2019; Mohite et al., 2019). In this apparatus, the grains are accommodated in the hole of the shear cell, then loaded with a certain normal weight, after which it is sheared by pushing one of the cells to move. This shearing process can calculate the magnitude of normal stress and shear stress. By varying the magnitude of the normal load, the related values of shear forces for each normal load applied will be obtained. Using Coulomb's theory, the angle of friction can be determined. It is done by graphically drawing the normal stress as the abscissa, and the shear stress as the ordinate, the angle of friction can then be determined from the slope of the line. Researchers in various works have also used this shear cell apparatus in their studies (Zou et al., 2020; Rasti et al., 2021; Tabari & Shooshpasha, 2021; de Oliveira et al., 2022; Zhu et al., 2022).

One of the most important factors which affect these angles is the moisture content of the grain. As the moisture content of the grain changes, the properties of the grain will also change, including the frictional properties of that grain. The effect of moisture content on the physical and mechanical properties of the grain is an important factor to be evaluated in determining machine design and storage facility (Jan et al., 2019). A similar statement is also conveyed by many other researchers (Dawange & Jha, 2019; Inekwe, 2019; Sadiku & Omogunsoye, 2021; Hasmadi, 2021; Wang et al., 2022). Therefore, it is necessary to find the relationship between φ and θ of the grains with their moisture contents. This research investigates the effect of moisture content on the φ and θ values of selected grains in Indonesia. The measurement methods, construction of the used apparatus, and the obtained values of these two parameters (φ and θ) will be very useful in developing modern bulk grain handling in Indonesia.

MATERIALS AND METHODS

Materials

In this research, indigenous Indonesian grains, including rough rice, white rice, corn, soybean, and coffee, each in three varieties or grain types, and three levels of moisture contents were used as the research samples. Two types of grains, i.e., *Koshihikar*i (japonica) and *Basmati* (indica) white rice, were not indigenous Indonesian grains, but they were included here to compare for indigenous white rice of *IR 64* (local). Those grain samples were chosen as they were the most commonly encountered grains in Indonesia; some were used as a staple food, such as white rice and corn, while others were mostly used as raw materials in several industries. The grain samples were bought from a local grain trader in Yogyakarta, Indonesia, while *Khosihikari* and *Basmati* white rice were bought through an online shop. Those grains were then transported to the laboratory, and some preparations began. The grains were cleaned manually to discard the impurities, broken grain, and discolored grain, and only healthy whole grain was used in the experiment. The grains went through heating and wetting to create the desired moisture content for the experiment. After the grains achieved the desired moisture contents, they were packaged in a plastic bag and stored in cold storage to be further used as the sample in the experiment. Each of the grains was measured for their frictional properties at three different moisture contents. Average values of major, intermediate, and minor diameters of the grains used in the research are presented in Table 1, while grain types, range of tested moisture contents, and the applied vertical loads used in the research are presented in Table 2.

Table 1

Average values of major, intermediate, and minor diameters of the grains used in the research

Grain Types	**a**			**b**			**c**		
	Moisture content (% wb)								
White rice	**9**	**14**	**19**	**9**	**14**	**19**	**9**	**14**	**19**
Local (*IR 64*)	0.698	0.710	0.725	0.234	0.238	0.245	0.174	0.178	0.185
Japonica (*Koshihikari*)	0.513	0.521	0.534	0.303	0.319	0.322	0.209	0.224	0.227
Indica (*Basmati*)	0.882	0.898	0.921	0.194	0.204	0.208	0.159	0.172	0.175
Rough rice	**14**	**20**	**25**	**14**	**20**	**25**	**14**	**20**	**25**
Local (*Inpari 19*)	0.983	0.999	1.023	0.281	0.276	0.282	0.211	0.222	0.231
Local (*Mentik wangi*)	0.870	0.891	0.922	0.326	0.338	0.338	0.220	0.235	0.243
Local (*Mapan 5*)	0.998	1.070	1.107	0.269	0.284	0.287	0.210	0.229	0.243
Corn	**14**	**20**	**25**	**14**	**20**	**25**	**14**	**20**	**25**
Dent corn (*Local-Hibrida*)	1.126	1.166	1.273	0.799	0.813	0.944	0.422	0.433	0.498
Flint corn (*Local-Mutiara*)	1.026	1.068	1.125	0.816	0.872	0.909	0.429	0.478	0.493
Popcorn (*Imported*)	0.823	0.899	0.951	0.620	0.687	0.729	0.412	0.411	0.478
Soybean	**10**	**13**	**16**	**10**	**13**	**16**	**10**	**13**	**16**
Local (*Galunggung*)	0.680	0.787	0.855	0.567	0.662	0.717	0.452	0.549	0.572

Table 1 *(Continue)*

Grain Types	**a**			**b**			**c**		
	Moisture content (% wb)								
Local-Black (*Malika*)	0.757	0.791	0.845	0.570	0.621	0.632	0.413	0.460	0.490
Imported (*America*)	0.735	0.833	0.909	0.676	0.722	0.768	0.587	0.634	0.675
Coffee	**9**	**14**	**19**	**9**	**14**	**19**	**9**	**14**	**19**
Local (*Robusta*)	1.034	1.213	1.247	0.831	0.919	0.935	0.535	0.573	0.625
Local (*Arabica*)	0.919	0.977	1.101	0.711	0.711	0.769	0.471	0.505	0.525
Local (*Excelsa*)	0.952	0.972	1.119	0.671	0.714	0.796	0.483	0.486	0.538

**a, b*, and *c* were the grain's major, intermediate, and minor diameters (cm), respectively.

Table 2

Grain types, range of tested moisture contents, and the applied vertical loads used in the research

Grains Type	**Moisture content (% wb)**	**Normal stress (kPa)**	
		φ	θ
White rice			
Local (*IR 64*) Japonica (*Koshihikari*) Indica (*Basmati*)	9, 14, 19	27.6, 34.6, 41.5	6.9, 10.4, 13.8
Rough rice			
Local (*Inpari 19*) Local (*Mentik wangi*) Local (*Mapan 5*)	14, 20, 25	20.8, 27.7, 34.6	6.9, 13.8, 20.8
Corn			
Dent corn (*Local-Hibrida*) Flint corn (*Local-Mutiara*) Popcorn (*Imported*)	14, 20, 25	20.8, 27.7, 34.6	6.9, 13.8, 20.8
Soybean			
Local (*Galunggung*) Local-Black (*Malika*) Imported (*America*)	10, 13, 16	27.6, 34.6, 41.5	6.9, 13.8, 20.8
Coffee			
Local (*Robusta*) Local (*Arabica*) Local (*Excelsa*)	9, 14, 19	27.6, 34.6, 41.5	6.9, 10.4, 13.8

The applied vertical stresses ranged from 20.75 to 41.53 kPa and 6.92 to 20.75 kPa for the measurement of φ and θ, respectively. Various normal stresses were used in the research, with normal stresses of 1.209 to 6.045 kPa for barley malt and malt crush (Vagová et al., 2019). Normal stresses ranged from 100 to 250 kPa for root-soil composite (Sui et al., 2021). It was also reported that in measuring the frictional properties of rape seed, the used normal stresses ranged from 25 to 100 kPa for φ and θ (Xu et al., 2019). The emphasis of this research was to find the relationship between moisture content and the frictional properties of the grains; for that reason, the moisture content level used was not the same for all the tested grains. However, it was considered that the range of moisture contents used in this research falls within the range of moisture contents commonly encountered in real postharvest handling practices in Indonesia.

Direct Shear Cell

The measurement of φ and θ were carried out using a direct shear cell constructed for this research (Figure 1). The main parts of this apparatus consist of upper and lower shear cells, loadcell (Keli, AMI Sensing Technology, 50 kg), threaded shaft, direct current (DC) electric motor (RWB, 12V), DC speed regulator (10A), AC to DC adapter (SPC 20A/12V), Analog Digital Converter (Single Channel 24 Bit Digital Interface with USB, Loadstar DI-1000U), and a computer. The shear cells' upper and lower cells were made from square-shaped steel with a circular hole at the center. The dimension of the upper cell was 24.5 × 15.5 × 1 cm, with a center hole diameter of 9.5 cm, whereas the lower cell was 18.5 × 12.5 × 1 cm, with a center hole diameter of 9.5 cm. The upper cell was supported by four roller wheels 3 cm in diameter and rested on an adjustable constructed rail, while the lower cell was fixed on the table surface. For the measurement of θ, the lower cell was replaced by the wall sample, where in this experiment, it was stainless steel plate 32 × 12 × 0.5 cm. This wall sample was also fixed on the surface of the table.

The vertical position of the upper cell could be adjusted by adjusting the height of the rail. This adjustment was needed to ensure no contact between the upper and lower cells in the measurement of φ or between the upper cell and the wall sample plate in measuring θ; this clearance was around 1mm. A load cell was used to measure the values of shearing force during measurement. This load cell was installed using 4 bolts on a specially constructed frame at the edge of the pushing rod. This shearing force was inputted to the Analog Digital Converter (interface) and finally recorded in the computer. The normal load was applied manually by putting a certain known weight on the surface of the grain in the upper cell. Normal loads were chosen as needed in the measurement, especially depending on the grain's types. In this study, a pre-experiment was carried out to determine the range of reasonable normal load to find a good measurement result. It was found that the normal load range for white rice, soybean, and coffee was the same, while rough rice had the same as corn. The normal load range was also different in the measurement of φ and θ. The shearing speed used in the measurement was around 3.0 mm/minute, which could be regulated by adjusting the DC speed regulator equipped in the apparatus.

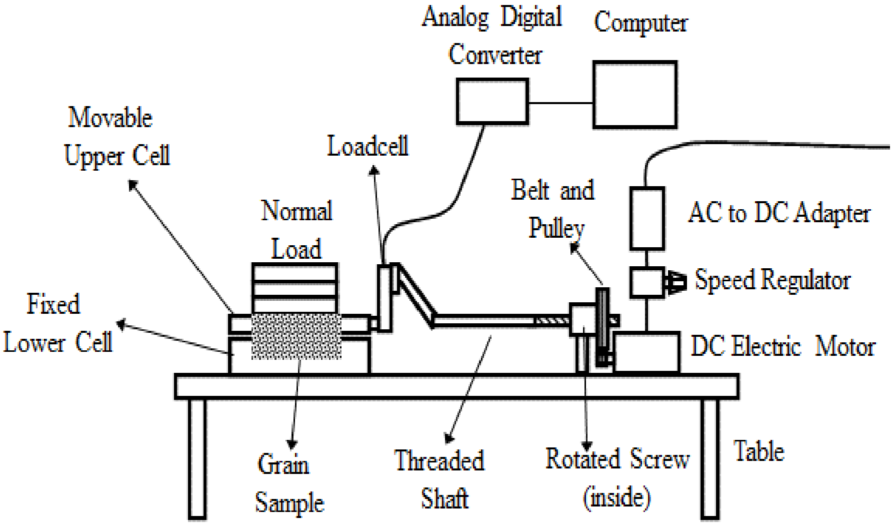

Figure 1. Constructed direct shear cell apparatus used in the experiment

Measurement of φ (Internal Friction Angle)

In this measurement, the first step was positioning the apparatus in the ready-for-measurement condition, with the upper and lower cell in parallel positions in the vertical direction, the grains were then poured into the hole of the cell, and the excess of the grain was gently cleaned using a steel plate so that it was aligned with the top cell surface. The desired normal/vertical load was gently put on the grain surface, then the apparatus was ready to be used for measurement. By turning on the electric motor, the threaded shaft would lengthen and push the upper cell, and the grain would be sheared. The shearing force was measured by loadcell and directly recorded in the computer through an ADC device. The shearing operation finished when the maximum shearing force had been achieved, as indicated by the computer monitor's constant value of the shearing curve. After the first measurement, the grain sample was removed, and the apparatus was again positioned in the ready-for-measurement condition. The next measurements were done the same way by using the new sample and replacing different normal loads as desired on the surface of the grains. Each grain sample was measured in three replications for each normal load used. Normal stress (σ) and shear stress (τ) were found by dividing normal load (P) and shear force (F) with the area of the cell hole (A), respectively. Assigning the shear stress as the ordinate and normal stress as the abscissa from the three measurements of different normal loads, a straight line could be drawn through the coordinate center, and the slope of that line was known as tan φ. The value of φ in degree*s* was determined as the arctan φ, as shown in Equations 1 to 3.

$$\sigma = \frac{P}{A} \tag{1}$$

$$\tau = \frac{F}{A} \tag{2}$$

$$\varphi = \arctan\left(\frac{\tau}{\sigma}\right) \tag{3}$$

This analysis meant that the grains were treated as non-cohesive material or had no cohesion stress in the following research. For dry granular materials with particles larger than 100 µm, the interparticle forces were often neglected when determining their mechanical properties, and the granular material was considered non-cohesive (Larsson, 2019). Furthermore, agricultural grains were free-flowing bulk materials, and in structural design, the cohesion between grains was usually not taken into account (Bucklin et al., 2013). Typically, grains did not have a significant, cohesive force to create surface tension between two types of granular materials (McLaren et al., 2019). It was also reported that for loose sand, which was comparable to dry agricultural grains, the cohesion force should be neglected (Elyashiv et al., 2020).

Measurement of *θ* (Wall Friction Angle)

The measurement of θ was also carried out using the same apparatus used in the measurement of φ. The important difference was the replacement of the lower cell with a piece of wall sample and fixing it beneath the lower surface of the upper cell. Height adjustment should be made to ensure that the wall sample did not touch the cell; this was done by adjusting the height of the sample wall or the upper cell. The procedures of measurement and determination of the value of θ were the same as measuring the φ above; the difference was only in the normal loads used. In this research, the sample of wall material was only a stainless-steel plate (32 × 12 × 0.5 cm) with an average surface roughness of 0.4294 µm. It was done with the consideration that there were quite a lot of grains tested, and the purpose was to find the trend of the effect of moisture content on θ and was not intended to collect the value of θ of those grains on various wall materials. As was in the measurement of φ, the measurement of θ was also to find the values of normal stress (σ) and shear stress (τ) for each sample. The value of θ was determined from Equation 4.

$$\varphi = \arctan\left(\frac{\tau}{\sigma}\right) \tag{4}$$

Data Analysis

In this research, the values of φ and θ of 15 types of grain were evaluated in relation to their three levels of moisture contents. The collected data were analyzed using linear regression analysis to find the relationship between the friction angles of the grains with the moisture content to find the regression equations and the coefficients of determination. Further, as the ranges of moisture content of the tested grains were not the same in this research, the value of φ and θ was not directly subjected to statistical analysis. However, the slopes of regression equations of those friction angles were used in the statistical analysis using a one-way analysis of CRD (Completely Randomized Design), and the means were compared with DMRT (Duncan's Multiple Range Test) with a significant level of 0.05.

RESULTS AND DISCUSSION

Internal Friction Angle (φ)

Figure 2 presented the results of φ values from the 15 tested grains in three different moisture contents. It could be observed that the value of φ of the tested grains differed considerably, ranging from 20.95^o for white rice (*Koshihikari*) at 9% moisture content to 31.89^o for local soybean (*Galunggung*) at 16% moisture content. All grains indicated a significant increase of φ values with the increase in moisture contents. Similar phenomena were also reported in several research works (Xu et al., 2019; Brar et al., 2016). It was suspected that increasing grain moisture content caused the grain surface to become wetter so that it would increase the cohesive forces between grains and finally produce a larger φ value. In the range of the tested moisture contents, the increments of the φ values ranged from 7.82% for dent corn (*Hibrida*) to 23.13% for coffee (*Excelsa*).

It was reported that when moisture content increased from 6,56 to 11.16% (wb), the value of φ for rape seed increased by 27.47, 17.68, 14.27, and 11.08% for normal stress used of 25, 50, 75, and 100 kPa, respectively (Xu et al., 2019). These increments were comparable with the results from this study. The trends of the increment of φ differed among the tested grains, as shown by the steepness of the slope of those lines. These slopes ranged from 0.159 to 0.598, with an average of 0.363, in which the smallest slope was for dent corn (*Hibrida*), and the largest was for coffee (*Excelsa*). The higher the slope, the more susceptible the value of φ to the change in moisture content, and vice-versa. It meant that the value of φ for coffee (*Excelsa*) was the most susceptible to the change in moisture content, while dent corn (*Hibrida*) was the least affected one. It was possible that coffee (*Excelsa*) easily absorbed the moisture which accumulated on the kernel's surface, causing an increase in its cohesion force and finally producing a high φ value, while the opposite condition occurred for dent corn (*Hibrida*).

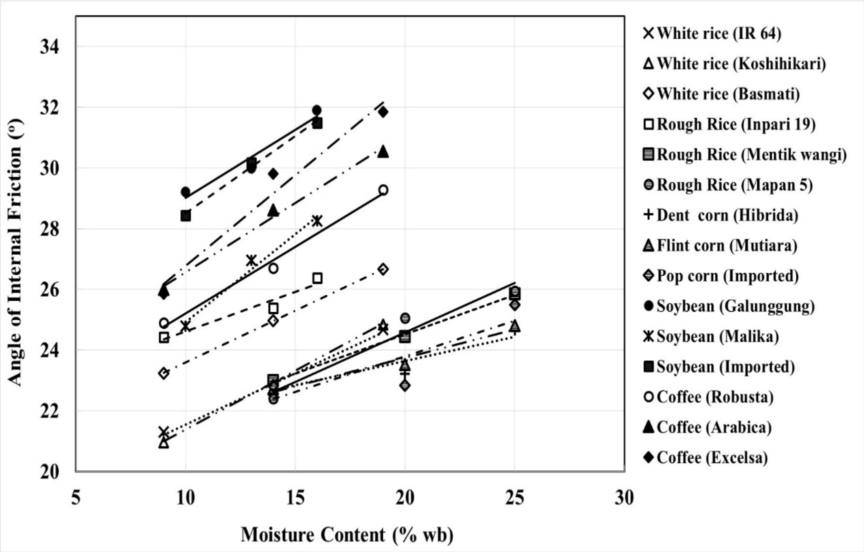

Figure 2. The values of φ as a function of moisture contents of the tested grains

The relationship between φ values and moisture contents of the grains could be expressed satisfactorily using linear regression, as indicated with high coefficients of determinations (Table 3). It was also reported that the relationship between φ and moisture content was linear for rape seed (Xu et al., 2019) and *Canarium schweifurthii* (Ehiem et al., 2015). Another study reported that the relationships between the coefficient of internal friction and moisture content were also linear for oat grain (Brar et al., 2016).

Statistical analysis indicated that the slopes of those regression lines were significantly influenced by grain type ($p<0.05$). This finding indicated that the frictional properties of each grain behaved differently in relation to the change in moisture content. This phenomenon was thought to be the effect of differences like the grain in relation to the change in its moisture content.

Table 3

Equations of the relationship between φ (y) and moisture content (x) of all tested grains

Grain Types	Equation	Coeff. of determination
White rice (*IR 64*)	$y = 0.337x + 18.164$	$R^2 = 0.99$
White rice (*Koshihikari*)	$y = 0.389x + 17.481$	$R^2 = 0.99$
White rice (*Basmati*)	$y = 0.343x + 20.16$	$R^2 = 1.00$
Rough rice (*Inpari 19*)	$y = 0.177x + 21.92$	$R^2 = 0.99$
Rough rice (*Mentik wangi*)	$y = 0.259x + 19.344$	$R^2 = 0.99$
Rough rice (*Mapan 5*)	$y = 0.326x + 18.067$	$R^2 = 0.95$

Table 3 *(Continue)*

Grain Types	**Equation**	**Coeff. of determination**
Corn (Dent corn, *Hibrida*)	$y = 0.159x + 20.457$	$R^2 = 0.85$
Corn (Flint corn, *Mutiara*)	$y = 0.187x + 20.005$	$R^2 = 0.96$
Corn (Popcorn, *Imported*)	$y = 0.235x + 19.096$	$R^2 = 0.71$
Soybean (*Galunggung*)	$y = 0.448x + 24.528$	$R^2 = 0.94$
Soybean (*Malika*)	$y = 0.578x + 19.145$	$R^2 = 0.98$
Soybean (*Imported*)	$y = 0.508x + 23.425$	$R^2 = 0.99$
Coffee (*Robusta*)	$y = 0.439x + 20.811$	$R^2 = 0.99$
Coffee (*Arabica*)	$y = 0.456x + 22.003$	$R^2 = 0.99$
Coffee (*Excelsa*)	$y = 0.598x + 20.798$	$R^2 = 0.97$

Table 4 compares the means using DMRT of the slopes for all tested grains. It was found that dent corn (*Hibrida*), rough rice (*Inpari 19*), flint corn (*Mutiara*), popcorn (*Imported*), and rough rice (*Metik wangi*) were not significantly different and belonged to the lowest values of line slope while soybean (*Malika*) and coffee (*Excelsa*) were not significantly different and had the largest slope values.

Table 4

Means comparison (DMRT) of the line slopes of the φ of the tested grains

Grain types	**N**	**Slope means**
White rice (*IR 64*)	3	0.3373^{cd}
White rice (*Koshihikari*)	3	0.3897^{def}
White rice (*Basmati*)	3	0.3429^{cde}
Rough rice (*Inpari 19*)	3	0.1766^{a}
Rough rice (*Mentik wangi*)	3	0.2586^{abc}
Rough rice (*Mapan 5*)	3	0.3256^{bcd}
Corn (Dent corn, *Hibrida*)	3	0.1591^{a}
Corn (Flint corn, *Mutiara*)	3	0.1873^{a}
Corn (Popcorn, *Imported*)	3	0.2350^{ab}
Soybean (*Galunggung*)	3	0.4482^{fg}
Soybean (*Malika*)	3	0.5861^{h}
Soybean (*Imported*)	3	0.5088^{gh}
Coffee (*Robusta*)	3	0.4385^{efg}
Coffee (*Arabica*)	3	0.4568^{fg}
Coffee (*Excelsa*)	3	0.5982^{h}

*The values followed with the same letter were not significantly different

For the same grain types, some of them were significantly different, while some of the others were the same. For example, white rice of *IR 64*, *Basmati*, and *Koshihikari* were not significantly different, and the same was true for corn grains. However, the coffee of *Excelsa* was significantly different from *Robusta* and *Arabica*; the same was true for rough rice and soybean grains.

Wall Friction Angle (θ)

Figure 3 presents the relationship between μ values and moisture contents for all tested grains. The same phenomenon could also be observed where the values of θ increased with moisture contents. The same phenomenon was also reported by other researchers (Dauda et al., 2019; Inekwe, 2019; Jan et al., 2019; Larsson, 2019; Mohite et al., 2019; Etim et al., 2021; Kopeć-Jarosz & Wójcik, 2021; Wang et al., 2022; Zhang et al., 2022). As can be observed, all the linear regression lines of the grains showed positive increments but differed in steepness, indicating that θ of the tested grains increased with moisture content. This increment was possibly caused by the fact that increasing moisture content would increase water content on the surface of the grain, causing the grain surface to become wetter, and this condition caused more intensive friction between the grain and the wall surface as the result of increasing adhesion force between the grain and wall sample. The same condition applied for φ values; the values of θ of the tested grains differed considerably, ranging from 10.83^o for rough rice (*Mapan 5*) at a moisture content of 14% to 24.76^o for white rice (*IR 64*) at 19% moisture content. However, as compared with the value of φ, the type of the grains and the values were different, where for φ, the lowest was 20.95^o for white rice (*Koshihikari*) at 9% moisture content, and the largest was 31.89^o for local soybean (*Galunggung*) at 16% moisture content. In general, the values of θ were considerably smaller as compared to the values of φ for all the grains tested.

The smoother sliding surface of the stainless-steel plate created less friction force to the grain than the friction force between the grain on itself and resulted in smaller values of θ. In the range of moisture contents tested, the increments of the μ values ranged from 1.521% for rough rice (*Inpari 19*) to 90.309% for white rice (*IR 64*), while in the same condition for φ, the values were 7.82% for dent corn (*Hibrida*) and 23.13% for coffee (*Excelsa*). White rice showed the largest increment, followed by soybean, coffee, and corn, whereas the smallest increments were found for rough rice. It was known that rice had an open surface so that when it was wet, the water would immediately react with the ingredients, making it stickier and causing an increase in its adhesion force and finally producing a high θ value as compared with the other tested grains. The opposite condition occurred in rough rice, as there was a husk layer on the grain.

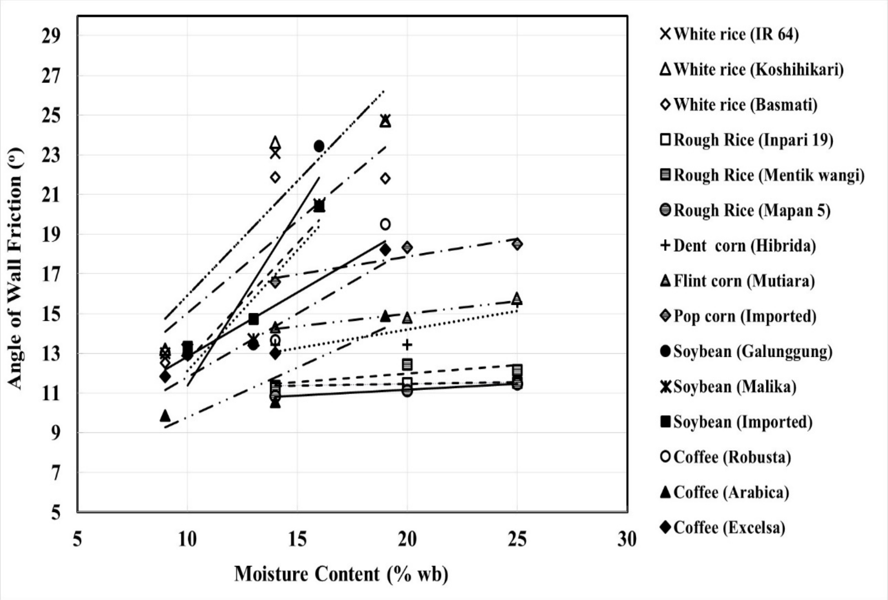

Figure 3. The values of θ as a function of moisture contents of the tested grains

The sliding friction coefficient of tiger nut on steel, aluminum, plexiglass, and polyurethane was reported to have a linear increase in moisture content (Zhang et al., 2022). The same phenomenon was reported for mucuna beans on plywood, aluminum, glass, galvanized steel, and rough wood (Etim et al., 2021). The trends of the increment of the θ values with the moisture contents also differed among the tested grains, as shown by the slopes of those lines. These slopes ranged from 0.016 to 1.745, with an average of 0.661, in which the smallest slope was for rough rice (*Mapan 5*) and the largest was for soybean (*Galunggung*). This phenomenon was also different from the condition for φ, where for φ values, these slopes ranged from 0.159 to 0.598, with an average of 0.363, in which the smallest slope was for dent corn (*Hibrida*), and the largest was for coffee (*Excelsa*). Table 5 summarizes the equations that explain the relationship between θ and the moisture content of the grains, along with their determination coefficients. These equations might approximate the values of θ of those grains on stainless steel for machinery or facility design. Statistical analysis indicated that the values of the slopes of those lines were significantly affected by the grain type ($p<0.05$). It strengthened the above finding that moisture content affected the frictional properties of the grains for the φ and θ in the same manner.

Table 5

Equations of the relationship between θ (y) and moisture content (x) of all tested grains

Grain Types	**Equation**	**Coeff. of determination**
White rice (*IR 64*)	$y = 1.175x + 3.8411$	$R^2 = 0.85$
White rice (*Koshihikari*)	$y = 1.153x + 4.3818$	$R^2 = 0.82$
White rice (*Basmati*)	$y = 0.929x + 5.7212$	$R^2 = 0.75$
Rough Rice (*Inpari 19*)	$y = 0.016x + 11.14$	$R^2 = 0.81$
Rough Rice (*Mentik wangi*)	$y = 0.086x + 10.279$	$R^2 = 0.59$
Rough Rice (*Mapan 5*)	$y = 0.059x + 9.9933$	$R^2 = 0.99$
Dent corn (*Hibrida*)	$y = 0.188x + 10.446$	$R^2 = 0.71$
Flint corn (*Mutiara*)	$y = 0.128x + 12.434$	$R^2 = 0.94$
Popcorn (*Imported*)	$y = 0.179x + 14.31$	$R^2 = 0.85$
Soybean (*Galunggung*)	$y = 1.745x – 6.0685$	$R^2 = 0.79$
Soybean (*Malika*)	$y = 1.215x – 0.0244$	$R^2 = 0.80$
Soybean (*Imported*)	$y = 1.180x + 0.8301$	$R^2 = 0.89$
Coffee (*Robusta*)	$y = 0.648x + 6.3424$	$R^2 = 0.82$
Coffee (*Arabica*)	$y = 0.501x + 4.7656$	$R^2 = 0.85$
Coffee (*Excelsa*)	$y = 0.639x + 5.4058$	$R^2 = 0.88$

From Table 6, it was also observed that for the same grain types, some of them were significantly different while some of the others were the same. Rough rice was not significantly different among all types tested, and the same was true for corn grains. However, *Arabica* coffee differed from *Excelsa* and *Robusta*; the same was true for white rice and soybean grains.

Table 6

Means comparison (DMRT) of the line slopes of θ of the tested grains

Grain types	N	Slope means
White rice (*IR 64*)	3	1.1750^{g}
White rice (*Koshihikari*)	3	1.1526^{g}
White rice (*Basmati*)	3	0.9298^{f}
Rough rice (*Inpari 19*)	3	0.0913^{ab}
Rough rice (*Mentik wangi*)	3	0.0848^{ab}
Rough rice (*Mapan 5*)	3	0.0587^{a}
Corn (Dent corn, *Hibrida*)	3	0.1877^{c}
Corn (Dent corn, *Hibrida*)	3	0.1877^{c}
Corn (Flint corn, *Mutiara*)	3	0.1282^{bc}
Corn (Popcorn, *Imported*)	3	0.1785^{c}
Soybean (*Galunggung*)	3	1.7451^{h}
Soybean (*Malika*)	3	1.2180^{g}
Soybean (*Imported*)	3	1.1803^{g}
Coffee (*Robusta*)	3	0.6476^{e}
Coffee (*Arabica*)	3	0.5007^{d}
Coffee (*Excelsa*)	3	0.6393^{e}

[*] The values followed with the same letter were not significantly different

CONCLUSION

It is concluded that both the values of φ and θ of the tested grains increased with moisture contents with different trends of increments. The relationship of those angles with moisture contents can be expressed as linear regression equations with high prediction coefficients. The slope of the regression lines for both φ and θ is found to be affected by grain type ($p<0.05$). For φ values, coffee (*Excelsa*) is the most susceptible to the change in moisture content, while dent corn (*Hibrida*) is the least affected one. For θ values, soybean (*Galunggung*) was the most susceptible to the change in moisture content, while rough rice (*Mapan 5*) was the least affected one.

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