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Effects of Moisture Content and Grain Type on Mechanical Properties of White Rice: Literature review and Experiment

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A B S T R A C T

The mechanical properties of agricultural grains are required in the design of agricultural processes and machinery. These properties are influenced by moisture content and grain type. This study aimed to determine the effect of moisture content and grain type on the mechanical properties of white rice. There are three different types of white rice, namely short-bold (Koshihikari), long-medium (IR 64), and very long-slender (Basmati) grains within three levels of moisture content of 9%, 14%, and 19% were used as the samples in the experiment. The experiment was designed into Completely Randomized Design, factorial 3 x 3. The dimension, internal friction angle, and rupture force of the grain samples were respectively measured using a digital calliper, direct shear cell apparatus, and compression test apparatus. It could be concluded that moisture content, grain type, and the interaction of these two factors significantly affected almost all parameters of the mechanical properties of white rice. Most of the relationships between the parameters of mechanical properties and moisture content could be expressed as linear equations.

A R T I C L E   I N F O

1. INTRODUCTION

Grain is known as a staple food for the majority of the world's population, which is why it is cultivated all over the world and covers the largest cultivated land. One of them is rice, which is a staple food, especially in Asian countries (Segal & Minh, 2019; Shakri *et al.*, 2021; Nueva *et al.*, 2022). It is estimated around 90% of rice is consumed in Asia (Bandumula, 2017). Similar statements were also expressed by other researchers (Muthayya *et al.*, 2014; Anthony *et al.*, 2016; Fukagawa & Ziska, 2019; and Lin *et al.*, 2022). Productivity, quality, availability, and sustainability must be ensured year-round to feed nearly half of the world's population.

The projected world milled (white) rice production in 2022/2023 will reach 512.44 million metric tons and during that period, rice production in Indonesia will reach 34.6 million metric tons, the highest in the Southeast Asia region. The high production of milled rice requires serious attention in every aspect to provide maximum benefits for people's lives. One form of attention is to further develop rice-related research to be able to increase both its quantity and quality to ensure its availability in the future. According to Esa *et al.* (2013), the demand for rice will remain high for decades to come.

White rice is the main product of paddy (*Oriza sativa* L) and paddy is the third most widely cultivated crop in the world. Based on its place of origin, rice is classified into three subspecies, namely indica, japonica, and javanica (Morishita *et al.*, 1987; Londo *et al.*, 2006; Dunna & Roy, 2013; Wang e*t al.*, 2014). Dunna and Roy (2013) stated that japonica rice is found mainly in Japan, javanica is mainly grown in Indonesia, and indica is cultivated all over tropical and sub-tropical Asia. In terms of shape, indica is slender somewhat flat grains, japonica is short roundish grains, and javanica is broad thick grains. These three types of rice grains have different characteristics. Their quality and quantity are heavily influenced by many factors, including the milling process applied. The waste resulting from the grain milling process will be produced in the form of husks, rice bran, and groats. The waste from this milling process has a high usefulness value. One of the milling wastes that get a lot of attention is the husk.

Kumar *et al.* (2013) used rice husk as a value-added raw material for various purposes, Anggraeni *et al.* (2022a) used husk as a mixture of vehicle brake pads. Anggraeni *et al.* (2022b) also used husk as a mixture of porous concrete, Anshar *et al.* (2016) used the husk as an activated carbon material, Nurjamil *et al.* (2021) utilized husks as a carbon source for batteries, and Wulandari *et al.* (2021) successfully used the rice husk as fuel for the stove. The properties of a material are very important to be figured out to characterize and utilize the material appropriately according to its potential. One of the important properties of organic materials including white rice is the physicochemical properties. One of the methods to characterize the physicochemical properties of the materials is Fourier Transform Infrared Spectroscopy (FTIR).

This method has been used intensively to characterize a wide variety of materials. Nandiyanto *et al.*, (2019) used FTIR for material characterization of *Lumbricus rubellus*, Thakur *et al.* (2019) used it to get characteristics of protein isolated from apricot, Panhwar *et al.* (2019) applied it on castor oil characterization, Obinna (2022) for researching human hair, Sukamto and Rahmat (2023) for compost products.

Based on the results of the FTIR spectra of white rice in the form of flour, the wavenumber of 4000–400 cm^{-1} was indistinguishable. At higher intensity, namely in the 3734.31 cm^{-1} regions, there is O-H stretching (water) in the material. The peak at 2019.54 cm^{-1}, showed the presence of an amine functional group as indicative of protein content (Thakur *et al.*, 2020). In addition to the FTIR characterization of the material. It can also be done using a Scanning

Electron Microscope (SEM). SEM will produce images of the sample by scanning the surface of the material. Based on this process, various signals containing information will be generated about the surface topography and composition of the sample. Akhtar *et al.* (2018) stated that SEM is an advanced and useful tool that is widely used to investigate surface phenomena of a material. While Thakur *et al.* (2020) stated that the investigation of the microstructure of a material can determine the microstructure, chemical composition, and physical properties of a material. Yolanda and Nandiyanto (2022) provided detailed steps on how to read and measure the diameter of material using SEM.

Martelo *et al.* (2021) used SEM to characterize the surface topography of coated paperboard, Khan *et al.* (2022) used SEM to investigate the microstructural changes of wheat flours and doughs, and Liu *et al.* (2019) used SEM for corn flour. Meanwhile, Rosli and Ain (2014) reported that the cross-sectional diameters for brown rice and white rice samples were in the range of 847 to 1000 μm. SEM can describe the microscopic conditions of a material surface in detail. In the field of agricultural engineering, this is very important concerning the frictional properties of agricultural grains, both internal friction, and wall friction. Both of these values are needed in the analysis of various agricultural equipment such as the design of silos for agricultural grain storage.

Many factors affect the properties of rice, but one of the most important factors in characterizing various properties of rice is the moisture content. In agricultural products, foods, and other biological materials, water is the most important component that practically forms all the important properties of these materials (Blahovec, 2007). Changes in the moisture content of rice will result in changes in the metabolic process in rice. At high moisture levels, metabolic activity will also increase and vice versa. Meanwhile, metabolic activity will directly affect various properties of the rice such as physical, mechanical, chemical, physiology, rheology, and others. Consequently, when measuring the properties of rice, it is necessary to always consider the effect of the moisture content of the rice. High moisture content in grains will cause high respiration and metabolic activity. Low moisture content respiratory activity will decrease and will be able to maintain product quality during storage (Lisboa *et al.*, 2017; Sa *et al.*, 2020).

There are various rice grains in the world and many bases for classifying rice are used such as place of origin, grain shape or size, starch content, aroma, milling grade, grain integrity, etc. As aforementioned, based on the place of origin, rice is divided into three subspecies or groups of different varieties, namely japonica, javanica, and indica. However, this classification cannot be a direct illustration of the geometry and dimension of the rice grain. To characterize the physical, mechanical, and rheological properties for engineering purposes, classification based on shape and size is considered more appropriate, because this classification method will be easier to visualize the grain appearance. Based on the grain length, the rice grain can be classified as short, medium, and long grains (Ikehashi, 2009; Dong *et al.*, 2010; Tamura *et al.*, 2021; Tchuisse *et al.*, 2020; Childs & Beau, 2021).

Specifically, the classification method is based on the shape and size of the rice grains as shown in **Table 1** (Normita & Cruz, 2002). This classification is considered to be more appropriate from an engineering point of view. Many studies have revealed the significant influence of grain shape and size on the physical, mechanical, chemical, and other properties of agricultural grains (Tengen *et al.*, 2008; El Fawal *et al.*, 2009; Emadi *et al.*, 2011; Firouzi 2014; Vega-Rojas *et al.*, 2016; and Soyoye 2018).

Table 1. Classification of rice according to the size and shape (Normita & Cruz, 2002).

Size Classification	
Size category	**Length (mm)**
Very long	More than 7.50
Long	6.61 to 7.50
Medium	5.51 to 6.60
Short	Less than 5.50
Shape Classification	
Shape category	**Length/Width Ratio**
Slender	More than 3.0
Medium	2.1 to 3.0
Bold	2.0 or less than 2.0

Based on the milling process carried out, rice is classified into rough, brown, and white. Rough rice is the term used for unprocessed rice, brown rice is rice that has undergone the husking process, and white rice is rice that has undergone a whitening process and is ready to be consumed. Generally, the rice traded in the market is in the form of white rice. Therefore, its characteristics must be identified to provide a better understanding of the quality attributes of white rice.

There are many quality attributes commonly used to characterize the quality of white rice, one of the most important properties of white rice and required by many designers and engineers is the mechanical properties of the grain. Mechanical properties are important parameters concerning many processing activities, machine design, and for the development of scientific theories. Similar statements have also been expressed by other researchers (Zareiforoush *et al.*, 2012; Nasirahmadi *et al.*, 2014; Haq *et al.*, 2015; Bhat & Riar 2016).

Many studies have been carried out to explore the properties of agricultural grains. However, there are still limited studies to investigate the mechanical properties of white rice. Kiani *et al.* (2009) worked on red bean grains, Sheifi and Alimardani (2010) reported the physical and mechanical properties of corn, Rodrigues *et al.* (2019) examined sorghum grain, Chandio *et al.* (2021) dealt with the mechanical properties of corn.

White rice grain is a biological material with a small size, its properties are not constant throughout its life, and therefore its mechanical properties are difficult to determine precisely. Its properties depend on many factors during post-harvest handling activities that affect the overall grain properties. One of the most important factors for most agricultural grains including white rice is the moisture content.

The moisture content is known to have a great influence not only on mechanical properties but almost all grain properties are affected by moisture content. Many reports indicate the significant effects of moisture content on grain properties (Kibar & Ozturk, 2008; Maksoud, 2009; Stasiak *et al.*, 2011; Babic *et al.*, 2011; Zareiforoush *et al.*, 2012; Kenghe *et al.*, 2012; Resende *et al.*, 2013; Horabik & Molenda, 2014; Chigbo, 2016; Feng *et al.*, 2019; Etim *et al.*, 2021; Dash *et al.*, 2021; Gierz *et al.*, 2022).

Since grain type and moisture content have a significant influence on grain properties, it is important that in any grain characterization, these two factors are considered. Therefore, it is important to investigate the mechanical properties of white rice concerning grain type and moisture content. This study aimed to determine the effect of grain type and moisture content on the mechanical properties of white rice by using Hertz's theory. The results of this study will provide

limited information related to the mechanical properties of white rice and are expected to be used as a reference in designing processes and machines, especially in the field of rice post-harvest activities.

2. LITERATURE REVIEW

Several reports on rice were carried out from various aspects. Shitanda *et al.* (2001), investigated the physical and mechanical properties of short grain (Akitakomachi) and long grain (*Delta* and *L201*) under a compression test. It was reported that long grain rice had a lower Poisson's ratio and higher yield stress compared to short grain rice.

Corrêa *et al.* (2007) examined the frictional and mechanical properties of three varieties of grain at three levels of the milling process. The results showed that the frictional properties of the three varieties decreased with the level of the milling process, while the rupture force was influenced by the level of the milling process but not influenced by the variety.

Parnsakhorn and Noomhorm (2008) investigated the physicochemical properties of two varieties of brown rice with high and low amylose contents during parboiled heat treatment at two different initial temperatures. It was reported that the yield of brown rice, yellowness, cooking time, and hardness of parboiled brown rice decreased while whiteness and water absorption increased compared to commercial parboiled rice. In addition, both varieties showed an increase in hardness values with increasing the initial temperature of the immersion water up to 80°C.

Zareiforoush *et al.* (2009) conducted research on the physical properties of two types of grain cultivars at five levels of moisture content. It was reported that the average length, width, thickness, equivalent diameter, surface area, volume, roundness, the weight of one thousand grains, angle of repose, and wall friction angle increased concerning moisture content.

Resende *et al.* (2013) investigated the mechanical properties of rough and dehulled rice grains at seven levels of moisture content. It was found that the rupture force increased with reducing moisture content from 37.2 to 70.6 N and 48.0 to 79.5 N for dehulled rice and rough rice, respectively. The same values for the average compression force ranged from 131 to 171 N and 203 to 283 N, and for proportional deformity, modulus ranged from 5.5×10^9 to 7.4×10^9 Pa and 9.5×10^9 to 12.3×10^9 Pa. Rough rice had more resistance to compression than dehulled rice.

Nasirahmadi *et al.* (2014) investigated the compressive strength properties of two varieties (*Tarom* and *Fajr*) of parboiled rough and milled rice. It was reported that in both parboiled and milled rice conditions, *Tarom* variety was stronger than *Fajr* variety. Increasing steaming time increased all investigated properties and increasing the moisture content decreased those properties.

Sarker (2017) compared the selected mechanical properties and qualities of *MR219* rice variety from six different drying methods. It was reported that bending strength and head rice yield were significantly affected by the drying method, but the drying method did not affect the modulus of elasticity of the sample. Comparable results were obtained for the degree of whiteness of rice and milling recovery.

Etim *et al.* (2021) researched the effect of moisture content on some mechanical properties and frictional properties of mucuna seeds. It was reported that the rupture force, deformation, and energy required to break the seed both on the main axis and minor axis were reduced as the moisture content increased. The relationships between the measured properties and moisture content were

satisfactorily expressed as linear regression equations. Although there have been many kinds of research conducted dealing with rice. However, none of them compare the mechanical properties of three different white rice at three different moisture contents using Hertz's theory. **Table 2** summarizes the literature review described above.

Table 2. Summary of literature review.

Author	Research topic/Question	Methodology	Finding
Shitanda *et al.* (2001)	Compressive strength properties of rough rice considering the variation of the contact area.	Experimentally measure the compressive strength of three varieties of rough rice (*Akitakomachi, Delta,* and *L201*). Then calculating compressive strength properties based on compression test results.	• Long grain rice had a lower Poisson's ratio and higher yield stress compared to short grain rice. • Contact area increases with increasing deformation
Corrêa *et al.* (2007)	Physical and mechanical properties in rice processing.	Measures the frictional and mechanical properties of three varieties of grain at three levels of the milling process.	• Frictional properties of the three varieties decreased with the level of the milling process. • Rupture force was influenced by the level of the milling process not by the variety.
Parnsakhorn and Noomhorm (2008)	Changes in physicochemical properties of parboiled brown rice during heat treatment.	Experimentally determination of the physicochemical properties of two varieties of brown rice with high and low amylose content during parboiled heat treatment at two different initial temperatures.	• The yield of brown rice, yellowness, cooking time, and hardness of parboiled brown rice decreased while whiteness and water absorption increased compared to commercial parboiled rice. • Both varieties showed an increase in hardness values with increasing the initial temperature of the immersion water increased to 80°C.
Zareiforoush *et al.* (2009)	Effect of moisture content on some physical properties of paddy grains.	Conducted measurement of the physical properties of two types of grain cultivars (*Alikazemi* and *Hasemi*) at five levels of moisture content.	• The average length, width, thickness, equivalent diameter, surface area, volume, roundness, the weight of one thousand grains, and angle of repose concerning moisture content. • Wall friction angle was also increased with moisture content.

Table 2 (Continue). Summary of literature review.

Author	Research topic/Question	Methodology	Finding
Resende *et al*. (2013)	Mechanical properties of rough and dehulled rice during drying.	Investigated the mechanical properties of rough and dehulled rice grains (cv. *Urucuia*) at seven levels of moisture contents by applying the compression test.	● Rupture force increased with reducing moisture content from 37.2 to 70.6 N and 48.0 to 79.5 N for dehulled rice and rough rice, respectively. ● Compression force ranged from 131 to 171 N and 203 to 283 N for dehulled rice and rough rice, respectively ● Proportional deformity modulus ranged from 5.5 x 10^9 to 7.4 x 10^9 Pa and 9.5 x 10^9 to 12.3 x 10^9 Pa for dehulled rice and rough rice, respectively. ● Rough rice had more resistance to compression force than dehulled rice
Nasirahmadi *et al*. (2014)	Modeling and analysis of compressive strength properties of parboiled paddy and milled rice.	Investigated the compressive strength properties of two varieties (*Tarom* and *Fajr*) of parboiled rough and milled rice	● Both parboiled and milled rice conditions of *Tarom* variety was stronger than *Fajr* variety. ● Increasing steaming time increased all investigated properties. ● Increasing the moisture content decreased those compressive strength properties.
Sarker (2017)	Mechanical property and quality aspects of rice dried in industrial dryers.	Compared the selected mechanical properties and qualities of *MR219* rice variety from six different drying methods.	● Bending strength and head rice yield were significantly affected by drying methods. ● The drying method did not affect the modulus of elasticity of the sample. ● Comparable results were obtained for the degree of whiteness of rice and milling recovery.
Etim *et al*. (2021)	Effect of moisture content on some mechanical and frictional properties of mucuna bean (*Mucuna crens*) relevant to its cracking.	Researched the effect of moisture content on some mechanical properties and frictional properties of mucuna seeds	● Rupture force, deformation, and energy to break the seed both on the main axis and minor axis were reduced as the moisture content increased. ● The relationships between the measured properties and moisture content were satisfactorily expressed as linear regression equations.

3. MATERIALS AND METHODS

3.1. Hertz's Theory

The foundation to carry out this research is Hertz's theory of convex bodies under compression. This method is considered objective, precise, and straightforward, so it is popular and used by many researchers (Khodabakhshian, 2011; Abasi & Minaei, 2014). Emadi *et al*. (2011) pointed out that Hertz's theory agrees well with the experimental results. This theory clearly describes the method used to calculate the parameters related to the mechanical properties of a convex body under compression. **Figure 1** illustrates a convex body under compression between two parallel plates.

The first step in the analysis is to determine the dimension of the grains to be tested. The radius of curvature for a small object such as agricultural grain can be determined using Equations (1) and (2) for minimum (R_1) and maximum (R_1') radius of curvatures, respectively. This means that by knowing the thickness (H) and length (L) of the grain then R_1 and R_1' of the grain can be calculated. These equations are also used by many other researchers, such as Kiani *et al*. (2009) for red bean grains, Emadi *et al*. (2011) for pumpkin seed, Voicu *et al*. (2013) for wheat, Abasi and Minaei (2014), and also Feng *et al*. (2019) for corn kernel, and Glangchai and Rangsri (2021) for glutinous rice.

$$R_1 = \frac{H}{2} \tag{1}$$

$$R_1' = \frac{H^2 + \frac{L^2}{4}}{2.H} \tag{2}$$

From known values of R_1 and R_1', then it can be used to calculate the value of $cos\ \theta$, which is the contact angle between the sample and the compression plate that can be determined using Equation (3). The value of $cos\ \theta$ then can be used to determine constants of *m*, *n*, and *k* from the table provided by Kosma and Cummingham.

$$Cos\ \theta = \frac{\left(\frac{1}{R_1} - \frac{1}{R_1'}\right)}{\left(\frac{1}{R_1} + \frac{1}{R_1'} + \frac{1}{R_2} + \frac{1}{R_2'}\right)} \tag{3}$$

As the value of m and n have been found and by knowing the compression force (F) from the measurement, then it can be used to calculate the major (a) and minor (b) semi-axis of the ellipse contact area using Equations (4) and (5), respectively. Whereas the values of k_1 and k_2 can be calculated using Equations (6) and (7), respectively.

$$a = m\left[\frac{3.F.(k_1+k_2)}{2}\left(\frac{1}{R_1} + \frac{1}{R_1'} + \frac{1}{R_2} + \frac{1}{R_2'}\right)^{-1}\right]^{1/3} \tag{4}$$

$$b = n\left[\frac{3.F.(k_1+k_2)}{2}\left(\frac{1}{R_1} + \frac{1}{R_1'} + \frac{1}{R_2} + \frac{1}{R_2'}\right)^{-1}\right]^{1/3} \tag{5}$$

$$k_1 = \frac{1-\vartheta_1^2}{E_1} \tag{6}$$

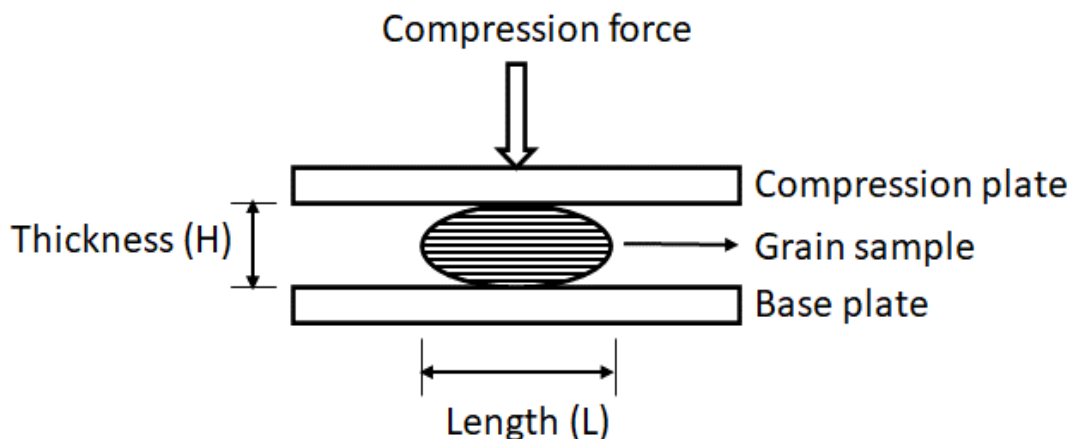$$k_2 = \frac{1-\vartheta_2^2}{E_2} \tag{7}$$

Figure 1. Illustration of the convex body under compression.

In these Equations (6 and 7), it is necessary to determine the values of Poisson's ratio (ϑ) and modulus of elasticity (E) for both grain and compression plate. According to Ding et al. (2013), Poisson's ratio of grain can be determined from the value of the angle of internal friction (ϕ) using Equation (8). This equation is also used by other researchers (Kibar et al., 2010; Kibar et al., 2014; Logo & Vasarhelyi, 2020).

$$\vartheta = \frac{1 - \sin\varphi}{2 - \sin\varphi} \tag{8}$$

The compression plate used in this study was made of steel with the modulus of elasticity and Poisson's ratio of 207 GPa and 0.3, respectively (Hussein, 2017).

These values are commonly used in many other studies considering the mechanical properties of steel in various situations (Sharma & Kumar, 2017; Deshmukh, 2019; Che et al., 2020; Yu et al., 2021). While modulus of elasticity of the grain is determined based on the research of Bamrungwong et al. (1987).

The modulus of elasticity of milled rice indica and japonica consistently decreased with increasing moisture content. Modulus of elasticity of indica milled rice *KDML 105* variety, length to width ratio 3.476, categorized as long-slender grain, comparable with *Basmati* in this experiment (**Table 3**) was 8.6 - 4.7 GPa for the range of moisture content from 10.394 to 15.825% (w.b).

While the same values for japonica milled rice (*Koshihikari*), length to width ratio 1.736, short-bold grain, the same variety as used in this experiment (**Table 3**) ranged from 5.2 - 3.0 GPa. Accordingly, the modulus of elasticity of the two kinds of grain types used in this experiment, namely very long-slender grain (*Basmati*) and short-bold grain (*Koshihikari*) can be determined using a linear regression equation.

Bamrungwong et al., (1987) also reported that *IR 60,* comparable with *IR 64*, a long-medium grain used in this experiment (**Table 3**), was classified as indica type. Thus, the modulus of elasticity of *IR 64* used in this experiment is assumed to be the same as the modulus of elasticity of very long-slender grain. Therefore, the modulus of elasticity of the three types of grain used in this experiment can be determined.

The contact area between the grain sample and compression plate is elliptical. The ellipse of this contact area can then be determined using Equation (9) and the maximum compressive stress can be calculated using Equation (10).

Finally, the value of the deformation at rupture can be calculated using Equation (11), where the values of R_u and R_u' are the same as R_1 and R_1', respectively. k_u is the same as k_1, which is determined based on the value of $\cos \theta$.

$$Ae = \pi. \, a. \, b \tag{9}$$

$$S_{max} = \frac{1.5 \cdot F}{\pi. \, a. \, b} \tag{10}$$

$$D = \left\{ \frac{0.338 \cdot F. \, (1 - \vartheta_1^2)}{E} . k_u^{\frac{3}{2}} . \left(\frac{1}{R_u} + \frac{1}{R_u'} \right)^{1/2} \right\}^{2/3} \tag{11}$$

3.2. Materials

Three different types of white rice grains, namely *Koshihikari*, *IR 64*, and *Basmati* in three different moisture content (*MC*) of 9%, 14%, and 19% (w.b) were used as samples in this study. White rice of *IR 64* was bought from a local market in Yogyakarta, Indonesia.

Meanwhile, *Koshihikari* and *Basmati* varieties were purchased through an online shop because they were not available in Indonesia. The three varieties of white rice were wetted and dried to achieve the desired moisture content intended in the study.

Table 3. Classification of white rice samples based on shape and size.

Grain Variety	Length (mm)	Length/Width	Category
Koshihikari	5.239	1.679	Short-bold grain
IR 64	7.111	2.979	Long-medium grain
Basmati	9.004	4.463	Very long-slender grain

Measurement of the moisture content of grain samples was determined using the gravimetric method. After the desired moisture content was reached, the three white rice samples were stored in a cold storage at around 5°C until they were used in the experiment.

Visually, the three of them had very different appearances, *Koshihikari* tend to be round-grained, *Basmati* was long and slender, while *IR 64* was between the two. It was figured out that in the range of moisture contents studied, the length(mm)/"length to width" ratio is "5.11-5.38"/"1.64-1.71", "6.95-7.26"/"2.94-3.04", and "8.80-9.23"/"4.38-4.71" for *Koshihikari*, *IR 64*, and *Basmati*, respectively.

The average values of these lengths and length-to-width ratio were used to classify three samples according to the classification proposed by Normita and Cruz, (2002). It was found that *Koshihikari* was categorized as short-bold grain, *IR 64* was long-medium grain, and *Basmati* was a very long-slender grain (**Table 3**).

It was observed that the three white rice types had very different values of length and length-to-width ratio and were categorized in three different shapes and sizes. It could also be reported that the change in moisture content of the grain samples did not change the category of that grain samples.

The determination of the shape and size based on the dimension measurement is about the same as the visual appearance. In other words, the classification of the grain based on the shape and size is the quantification of the visual appearance.

Furthermore, from this classification, it can be observed that the three types represent three different grain appearances commonly encountered in post-harvest handling practices, as short, long-medium, and very long grains. *Koshihikari* represents short grain, *IR 64* represents medium to long grain, and *Basmati* represents very long grain. Mir *et al.* (2013) reported that the physical dimensions and size of paddy and brown rice from different cultivars varied significantly.

3.3. Apparatus

To carry out the research, two main apparatus, namely direct shear cell and compression test apparatus, have been made. Construction of the direct shear cell mainly consisted of lower and upper shear cells, pushing rod, DC electric motor (RWB 12V), load cell (Keli, AMI Sensing Technology, 50 kg), speed regulator, AC to DC adaptor (20A 12 V), Analog Digital Converter (ADC, Loadstar DI-1000U), and computer.

These components were then assembled to construct a direct shear cell apparatus as presented in **Figure 2**. In principle, when the motor was turned on, it would rotate the screw through a belt and pulley transmission, causing the pushing rod to move horizontally and push the upper shear cell.

The magnitude of the shear force was measured by a load cell and recorded into the computer through an ADC. Whereas, normal load over the sample tested was applied manually.

The compression test apparatus consisted of a threaded pushing rod, DC electric motor (RWB 12V), sprocket-chain transmission, compression plate, loadcell (Loadstar 100 kg), AC to DC adaptor (12V), on-off button, speed regulator (10A), steel frame, Analog Digital Converter (ADC, Loadstar DI-1000U), and computer (**Figure 3**).
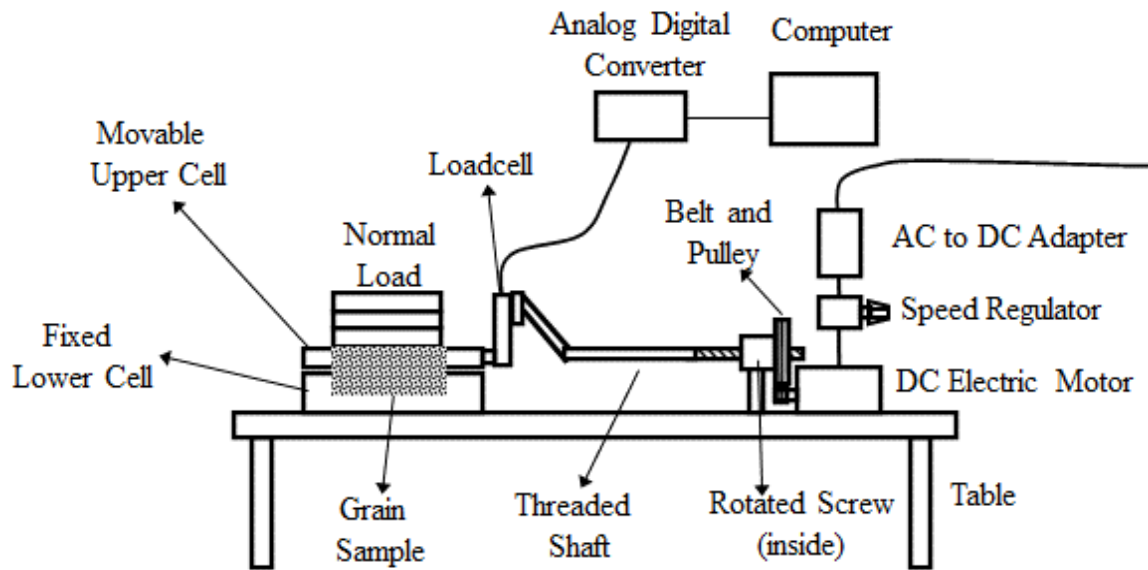
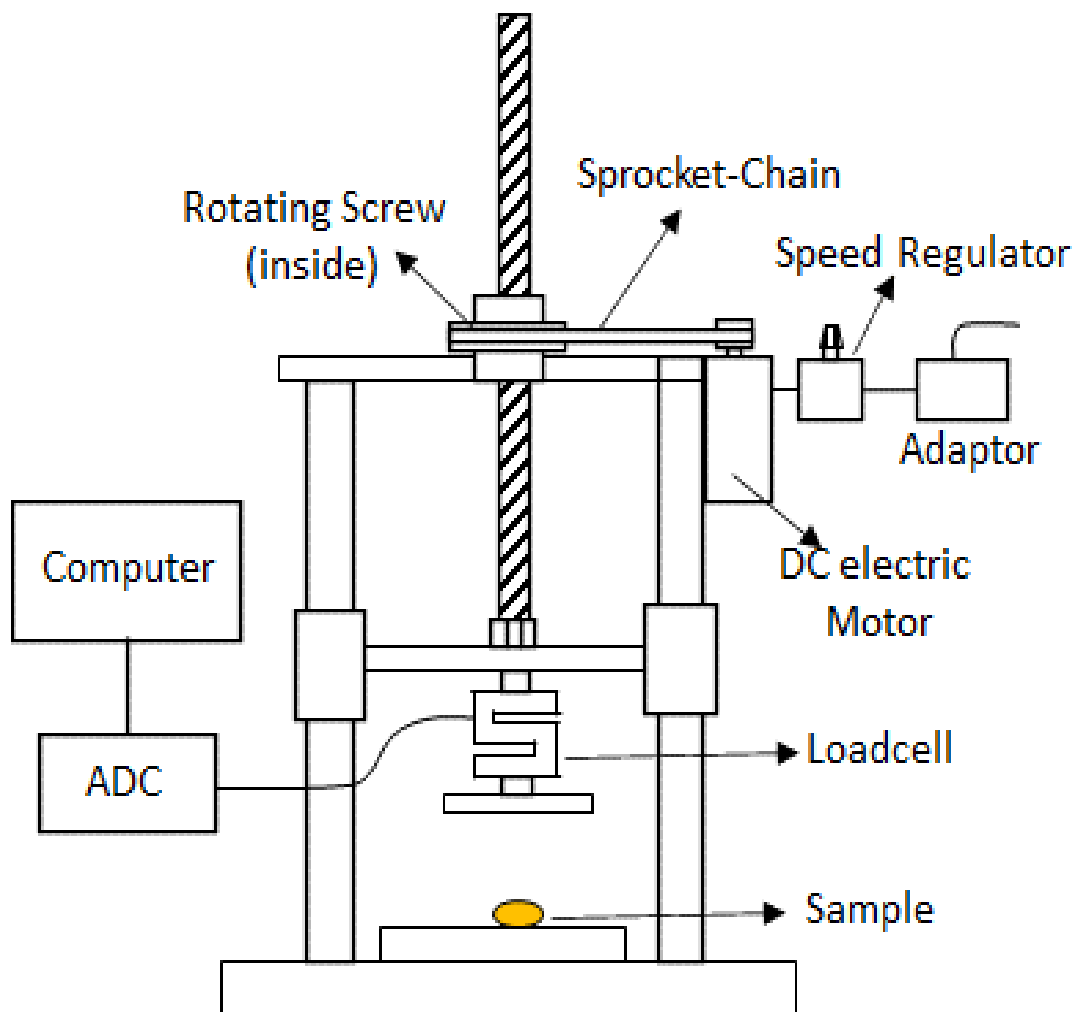**Figure 2.** The direct shear cell was used to measure the angle of internal friction.

Figure 3. The compression test apparatus used to measure rupture force.

The pushing rod was connected to a horizontal steel bar with sliders resting at the cylindrical vertical frame to guide the direction of the pushing rod vertically. A load cell was installed at this horizontal steel bar then a compression plate was placed at the lower part of the load cell. When the electric motor is turned on, it rotated the screw in the roller through the sprocket and chain transmission system, this caused the pushing rod to move vertically downwards and compressed the grain sample. The magnitude of the compression force would be recorded in the computer through an ADC.

3.4. Methods

The dimensions of the grain sample consisted of length (*L*), width (*W*), and thickness (*H*) were measured using a digital caliper. These data mainly would be used to calculate the radius of curvature of the grain, which was required to determine the ellipse contact area through several steps of calculations. These data were also used to classify the grain sample based on grain length as well as the ratio of length to width of the grain samples. Measurement of the angle of internal friction was carried out using a direct shear cell. The grain was poured into the hole of the shear cell, a certain known vertical load was then applied to the surface of the grain sample. After ADC was set in the ready position, then shearing was done by pushing the upper cell until failure occurred. The magnitude of the shearing force would be recorded on the computer. In the following research, three different normal loads of 20, 25, and 30 kg were used.

Measurement of rupture force was done using compression test apparatus. A single grain of white rice sample was placed on the base of the compression test apparatus in its natural resting position, then the compression plate was adjusted to slightly touched the top surface of the grain sample. The ADC was set to zero or in calibrated condition.

Afterward, the compression was done by turning on the electric motor. The compression process was stopped when the grain sample was broken. Compression force and sampling time would be recorded on the computer for further usage in the analysis. This procedure was similar to the method used by Bagheri *et al.* (2011) in determining the mechanical properties of brown rice grain.

3.5. Analysis

The data from this experiment were subjected to analysis of variance using Completely Randomized Design, factorial 3 x 3 with three replications. While a means comparison was carried out using Duncan's Multiple Range Test (DMRT) with a significant level of 0.05. The same replication was also used by Dong *et al.* (2010) for rice fissuring study, Wasala *et al.* (2012) in determining the coefficient of static friction of bananas, and Moya *et al.* (2013) in studying the mechanical properties of some granular materials, Altuntas *et al.* (2013) in characterizing medlar fruit, and El-Hamed (2015) in characterizing morphological and chemical variation of *Cucurbita pepo* seeds.

4. RESULTS AND DISCUSSIONS

In this study, the mechanical properties of three different types of white rice in three levels of moisture content have been investigated. These properties are represented by R_1, R_1', φ, ϑ, F, a, b, Ae, S_{max}, and D. The values of F, a, b, Ae, S_{max}, and D were determined at the maximum conditions when the grain was rupture in the compression test. **Figure 4** presents a summary of the changes in the mechanical properties with moisture content for the three types of grain. **Tables 4** and **5** summarize the DMRT results of the properties investigated by grain type and moisture content, respectively. Whereas **Table 6** presents the relationship equation of the investigated properties with the moisture content.
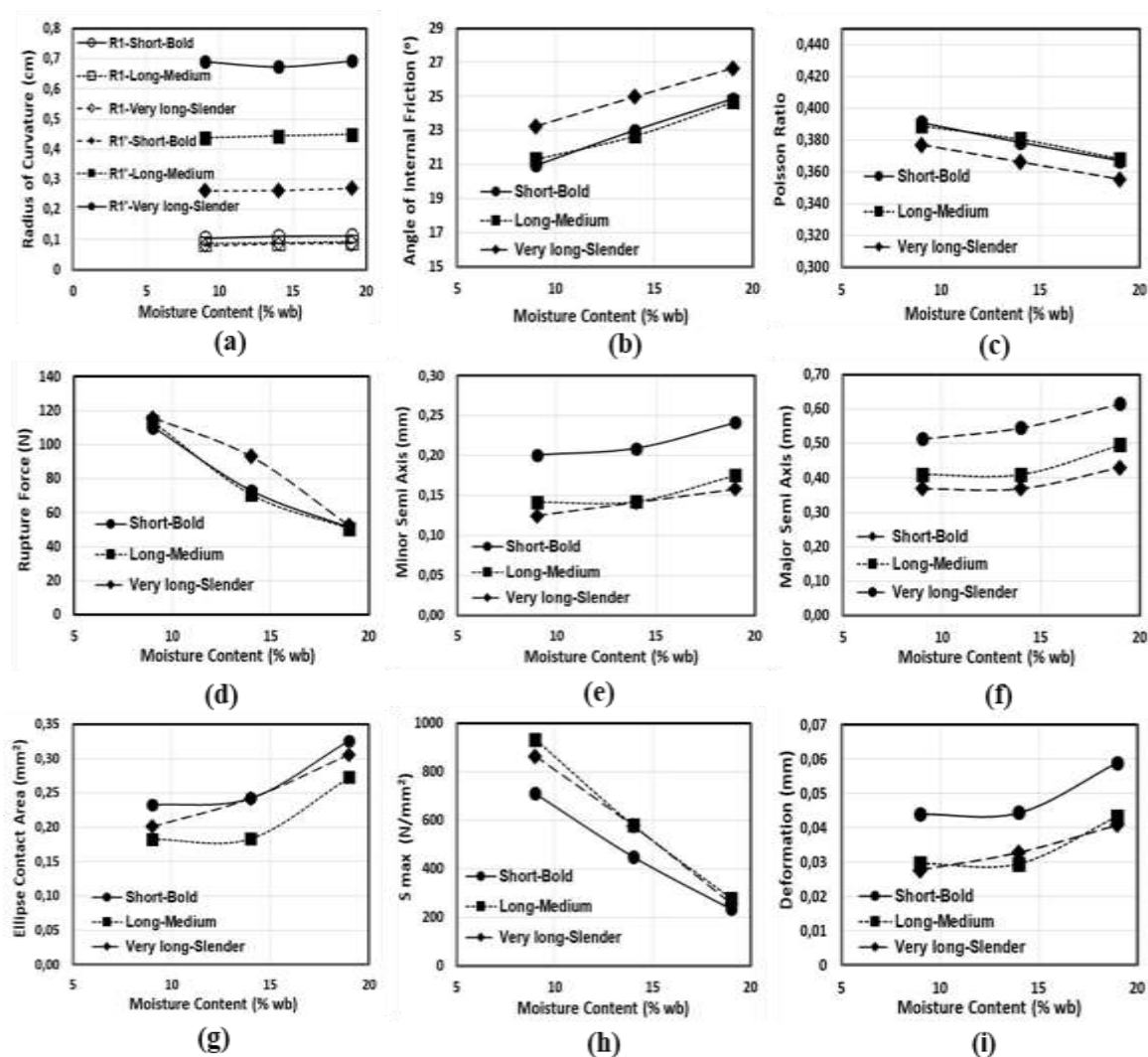
Figure 4. Observed mechanical properties as a function of moisture content: **(a)** Minimum and the maximum radius of curvature (R_1 and R_1'), **(b)**. Internal friction angle (φ), **(c)**. Poisson's ratio (ϑ), **(d)**. Rupture force (F), **(e)**. Major semi-axis (a), **(f)**. Minor semi-axis (b), **(g)**. Ellipse contact area (Ae), **(h)**. Maximum pressure (S_{max}), and **(i)**. Deformation (D).

Table 4. The results of DMRT analysis for all parameters according to grain type.

Parameter	Short bold grain	Long medium grain	Very long slender grain
R_1 (cm)	0.000895[a]	0.000843[b]	0.001100[c]
R_1' (cm)	0.00265[a]	0.00443[b]	0.00686[c]
φ (°)	22,937[a]	22,886[a]	24,959[b]
ϑ (-)	0.379[a]	0.379[a]	0.366[b]
F (N)	78.065[a]	78.306[a]	87.170[b]
a (mm)	0.389[a]	0.439[b]	0.558[c]
b (mm)	0.217[a]	0.153[b]	0.142[c]
Ae (mm²)	0.267[a]	0.213[b]	0.249[c]
S_{max} (N/mm²)	465.446[a]	596.496[b]	565.872[c]
D (mm)	0.0492[a]	0.0342[b]	0.0338[b]

*) values in the same row followed with the same letter were not significantly different at α=0.05.

Table 5. The results of DMRT analysis for all parameters according to moisture content.

Parameter	MC 9%	MC 14%	MC 19%
R_1 (cm)	0.000903[a]	0.000956[b]	0.000978[c]
R_1' (cm)	0.00464[a]	0.00460[a]	0.00471[b]
φ (°)	21,832[a]	23,552[b]	25,399[c]
ϑ (-)	0.386[a]	0.375[b]	0.363[c]
F (N)	113.196[a]	78.893[b]	51.452[c]
a (mm)	0.431[a]	0.442[b]	0.514[c]
b (mm)	0.156[a]	0.164[b]	0.192[c]
Ae (mm²)	0.205[a]	0.223[b]	0.302[c]
S_{max} (N/mm²)	835.516[a]	535.312[b]	256.986[c]
D (mm)	0.0338[a]	0.0356[b]	0.0478[c]

*) values in the same row followed with the same letter were not significantly different at α=0.05.

Table 6. Regression equations of the relationship between parameters of mechanical properties (y) and moisture content (x).

Parameter	Short-bold grain	Long-medium grain	Very long-slender grain
R_1 (cm)	y = 0.0008x + 0.0731 $R^2 = 0.898$	y = 0.0006x + 0.0818 $R^2 = 0.976$	y = 0.0008x + 0.0731 $R^2 = 0.898$
R_1' (cm)	y = 0.0009x + 0.2531 $R^2 = 0.899$	y = 0.0011x + 0.428 $R^2 = 0.991$	y = 0,0008x² - 0,0218x + 0,824 $R^2 = 1.000$
ϕ (°)	y = 0.3897x + 17.481 $R^2 = 0.999$	y = 0.3373x + 18.164 $R^2 = 0.989$	y = 0.3429x + 20.16 $R^2 = 1.000$
ϑ (-)	y = -0.0024x + 0.4127 $R^2 = 0.999$	y = -0.0021x + 0.4085 $R^2 = 0.987$	y = -0.0022x + 0.3967 $R^2 = 1.000$
F (N)	y = -5.9201x + 160.95 $R^2 = 0.977$	y = -5.9201x + 160.95 $R^2 = 0.977$	y = -6.3336x + 175.84 $R^2 = 0.974$
a (mm)	y = 0.0061x + 0.3047 $R^2 = 0.751$	y = 0.0085x + 0.3195 $R^2 = 0.745$	y = 0.0102x + 0.4157 $R^2 = 0.956$
b (mm)	y = 0.0041x + 0.1602 $R^2 = 0.896$	y = 0.0034x + 0.1059 $R^2 = 0.764$	y = 0.0034x + 0.0944 $R^2 = 1.000$
Ae (mm²)	y = 0.0015x² - 0.0319x + 0.4007 $R^2 = 1.000$	y = 0.0018x² - 0.0409x + 0.4063 $R^2 = 1.000$	y = 0.0105x + 0.1029 $R^2 = 0.985$
S_{max} (N/mm²)	y = -47.584x + 1131.6 $R^2 = 0.9971$	y = -65.306x + 1510.8 $R^2 = 0.9978$	y = -60.67x + 1415.2 $R^2 = 0.9990$
D (mm)	y = 0.0003x² - 0.0065x + 0.079 $R^2 = 1.000$	y = 0.0003x² - 0.0065x + 0.065 $R^2 = 1.000$	y = 0.0013x + 0.0153 $R^2 = 0.983$

4.1. The Minimum and the Maximum Radius of Curvatures

From grain dimensions, the values of minimum (R_1) and maximum (R_1') radius of curvatures of the grain sample were respectively calculated using Equations (1) and (2). The R_1 was calculated based on the thickness of the grain sample, while R_1' was calculated based on the thickness and length of the grain sample. **Figure 4(a)** presents the values of R_1 and R_1' as the function of moisture content for the three types of grain. It could be observed that R_1' was considerably higher than R_1, as stated in the theory.

Both radii slightly increased with moisture contents but the rates of increase were not the same. It was reasonable since the moisture content of the grain increased, the

volume of the grain would increase too, resulting in longer and thicker grain size, and finally increased the values of R_1 and R_1'. Resende *et al.* (2013) stated that the radius of curvature of rice varied with moisture content. However, there was no certain pattern observed. It was also observed that very-long slender gain had the largest value of R_1' but the smallest value of R_1 this phenomenon reflected that the shape of this grain was very long and thin.

Bamrungwong *et al.* (1987) found that the radius of curvature of indica rice was considerably different from japonica rice. Statistical analysis among the R_1 values indicated that grain type and moisture content significantly affected the value of R_1, however, there was no interaction between the two factors (p<0.05). Whereas for the R_1' values, it was found that grain type, moisture content, and interaction of these two factors significantly affected R_1' (p<0.05). From means comparison analysis using DMRT, it was obtained that the values of R_1 of the three-grain types and the three moisture contents tested differed from each other (**Tables 4** and **5**).

The relationship between R_1 and R_1' with the moisture content could be expressed satisfactorily as linear regression equations, except for the equation of R_1' for the very long-slender grain which was better to be expressed as a quadratic polynomial equation (**Table 6**). Zuomei *et al.* (2015) found that R_1 tended to increase, while R_1' had no certain pattern with the increase in moisture content for milled grain.

4.2. Angle of Internal Friction

In this study, the internal friction angle (φ) was measured using a direct sheal cell apparatus. It was found that φ increased with moisture content with the rate of increment almost the same for the three-grain types. **Figure 4(b)** presents the values of φ for the three-grain types as the function of moisture content. Some researchers also reported the phenomenon of increasing φ with moisture

content, Kibar and Ozturk (2008) for soybean, Kibar *et al.* (2010) for rough rice, Balasubramanian and Viswanathan (2010) for milled, Ozturk and Esen (2013) for corn, Klinkesorn *et al.* (2004) for wheat, and Chigbo (2016) for soybean.

The increase in φ value due to the increase in moisture content was probably due to the surface of the seeds getting wetter at higher moisture content, thereby increasing the cohesive forces between grains which would further increase the φ value. Statistical analysis revealed that grain type, moisture content, and the interaction of these two factors significantly affected φ values (p<0.05).

The DMRT analysis revealed that long-medium grain was not significantly different from short-bold grain, while those two-grain types significantly differed from very long-slender grain type (**Tables 4** and **5**). The relationship between φ and moisture content could be expressed as linear equations (**Table 6**). Kibar (2010) also reported that φ of rice grain increased with moisture content in a linear relationship. Bahesti *et al.* (2014) also reported a linear increase of φ with moisture content for two wheat varieties of *Durum* and *Ghods*.

4.3. Poisson's Ratio

The φ values obtained were then used to calculate Poisson's ratios (ϑ) by applying Equation (8). It could be observed that the resulting ϑ values ranged from 0.355 to 0.391, where these values were in the range of ϑ which was commonly suggested in many research reports. The value of Poisson's ratio ranged from 0 to 0.5. Many research works also reported the value of ϑ in that range for different agricultural products, Shitanda *et al.* (2002) for rough rice, Molenda and Stasiak (2002) for wheat, Burubai *et al.* (2008) for nutmeg, Kiani *et al.* (2009) for red bean grain, Sarnavi (2013) for wheat, Moya *et al.* (2013) for barley, oats, sunflower, lentil, wheat, and corn, and Neto *et al.* (2016) for rice. This meant that the suggested equation to

compute ϑ was in good agreement with much literature and therefore could be used to estimate the value of ϑ, especially for grain material. It was also observed that the values of ϑ decreased as the moisture contents increased (**Figure 4(c)**), this was an opposite trend as compared with φ. In the other words, the larger the value of φ, the smaller the value of ϑ.

The statistical analysis resulted that grain type, moisture content, and the interaction of these two factors significantly affected ϑ values (p<0.05). It was also observed that the values of ϑ for short-bold and long-medium grains were not significantly different but differed with very long-slender grains and had higher values (**Tables 4** and **5**). This was in agreement with the work reported by Shitanda *et al.* (2002) that the short rough rice grain of *Akitakomachi* had a larger value of ϑ than the long rice grains of *Delta* and *L201*. Further, the relationship between ϑ and moisture content could be expressed as a linear equation (**Table 6**). Kiani *et al.* (2009) also found that the value of ϑ for red grain beans increased linearly with moisture content.

4.4. Rupture Force

The compressive strength of the grain samples was measured to determine the maximum force (*F*) when the grain sample was broken. The results revealed that the rupture forces of the samples also varied according to moisture content and grain type. **Figure 4(d)** presents the rupture force of the grains samples as the function of moisture content. The rupture force of all three-grain types was shown to decrease as the moisture content increased. The same phenomenon was also observed by many other researchers, Altuntas and Yildis (2007) for faba bean grain, Khodabakhshian *et al.* (2011) for sunflower seeds, Zareiforoush *et al.* (2012) for paddy, Resende *et al.*, (2013) for rough rice, Nasirahmadi *et al.* (2014) for paddy, Zoumei *et al.* (2015) for milled grain, Nyorere and Uguru (2018) for gmelina seed,

Mohite *et al.* (2019) for tamarind seed, Rodrigues *et al.* (2019) for sorghum, Wang and Wang (2019) for corn, and Etim *et al.* (2021) for mucuna bean. It was also observed that the three-grain types had almost the same values of *F*, except for very long-slender grain at a moisture content of 14%, which was quite larger as compared with short-bold and long-medium grains.

These results informed that the rate of decreasing *F* values with increasing moisture content for very long-slender grains was smaller as compared with short-bold and long-medium grains. Statistical analysis revealed that grain type, moisture content, and the interaction between these two factors significantly affected *F* values (p<0.05). From means comparisons, it was obtained that short-bold and long-medium grains were not significantly different but differed with very long-slender grain types. The very long-slender grain was found to have a larger value of *F* as compared to short-bold and long-medium grains (**Tables 4** and **5**). Shitanda *et al.* (2002) reported that rupture force for a long grain of rough rice was higher than that of short grain rice. The relationships between *F* and moisture content for the three-grain types were adequately expressed as linear equations (**Table 6**). Bagheri *et al.* (2011) reported that the relationship between *F* value of brown rice from 12-grain varieties and moisture content was linear and the *F* value decreased with increasing moisture content for rice. Resende *et al.* (2013) also reported that *F* decreased linearly with increasing moisture content for rough and dehulled rice. Meanwhile, Seifi and Alimardani (2010) reported that *F* of corn grain increased with moisture in the quadratic polynomial.

4.5. Major and Minor Semi-Axis

Minor semi-axis (*b*) is the shorter radius of the ellipse contact area between the compression plate and grain sample. This value is calculated using Equation (5) and the results are depicted in **Figure 4(e)**. It could be

observed that the value of b tended to increase with moisture content. Short-bold grain was also observed to have the largest b value, followed by long-medium grain, and the smallest was for very long-slender grain. This was in contrast with the values of a, this meant that as the length of the grain was shorter the value of b of that grain would be larger.

Short-bold grain had the largest R_1 but the smallest value of R_1', this caused the value of b for japonica to be the largest. On the contrary, the very long-slender grain had the smallest R_1 but the largest R_1', because the value of a was the largest. Statistical analysis showed that grain type, moisture content, and the interaction of these two factors significantly affected b values ($p<0.05$). Zoumei *et al.* (2015) reported a significant effect of moisture content on b values for milled grain. Means comparisons revealed that the values of b differed for the three-grain types, and the same was true for the three moisture contents tested (**Tables 4** and **5**). A linear relationship between b and moisture content was found for the three-grain types tested (**Table 6**).

Major semi-axis (a) is the longer radius of the ellipse contact area between the compression plate and grain sample. This value is calculated using Equation (4) and the results are depicted in **Figure 4(f)**. It could be observed that this value increased with the moisture content at almost the same slope for the three-grain types. The very long-slender grain had the largest a value, followed by the long-medium grain and the smallest was for short-bold grains. This finding seemed to have a strong correlation with the length of grain types, where the longer the length of the grain, the larger the value of a for that grain.

Statistical analysis indicated that grain type, moisture content, and the interaction of these two factors significantly affected the values of a ($p<0.05$). Zoumei *et al.* (2015) found that moisture content significantly affected the value of a for milled grain.

Tables **4** and **5** show the results of mean comparison using DMRT for the values of a for the three-grain types tested. Similar to the value of b, the relationship between a and moisture content could be satisfactorily expressed using linear equations (**Table 6**).

4.6. Ellipse Contact Area

Using Equation (9) the ellipse contact area (Ae) between the grain sample and the compression plate at rupture can be determined. **Figure 4(g)** presents the results of Ae values for the three types of grain as a function of moisture content. It was found that the value of Ae increased along with moisture content. Short-bold grain had the largest Ae followed by very long-slender grain and the smallest was for long-medium grain. This finding is consistent with the results reported by Shitanda *et al.* (2002) where short rough rice grain was found to have a slightly higher contact area compared to long rice grain. Statistical analysis showed that grain type, moisture content, and the interaction of those two factors significantly affected Ae values ($p<0.05$).

Means comparison of Ae values for the three-grain types tested informed that Ae differed both according to the grain type and the moisture content (**Table 4** and **5**). The relationship between Ae and moisture content for very long-slender grain tended to have a linear pattern. However, short-bold grain and long-medium grain were better to be expressed as the polynomial equations (**Table 6**). These results showed that for short-bold grain and long-medium grain types, the values of Ae were almost constant from 9 to 14% of moisture contents, however, increased quite large beyond 14% of moisture content.

4.7. Maximum Pressure

S_{max} is the maximum pressure in the grain material when the grain is compressed and this occurs at the center of the contact point between the grain and the compression plate. S_{max} is calculated from the value of

compression force at rupture divided by Ae. **Figure 4(h)** presents the values of S_{max} for the three-grain types as the function of moisture content. It could be seen that S_{max} decreased along with the increase in moisture content. It was reasonable since as the moisture content increased, the grain would become softer and their strength becomes weaker, as a result, their resistance to the compression stress would also decrease.

The same phenomenon was observed by Zoumei *et al.* (2015) for milled grain and Buggenhout *et al.* (2013) for raw and parboiled rice. It could also be found that short-bold grain seemed to have the lowest value of S_{max}, while long-medium and very long-slender grains were almost the same. These findings were in agreement with the one reported by Bamrungwong *et al.* (1987) for rice grain, where long grain had a larger breaking force than short grain. Visually could be observed that short-bold grains had a smaller grain size as compared to long-medium and very long-slender grains. This smaller grain size might need lower compression stress to break than the larger ones, which caused the lower value of S_{max} for short-bold grain type. Statistical analysis showed that grain type, moisture content, and the interaction of these two factors significantly affected S_{max} values (p<0.05). From the comparison of the means, the three-grain types were different from each other, and the same was true given the moisture content tested (**Tables 4** and **5**). The relationship between S_{max} and the moisture content of the three-grain types was also found to be linear (**Table 6**).

4.8. Deformation

Deformation (*D*) of the grains is a decrease in grain height or thickness when the grain is being compressed, and this value is calculated using Equation (11). **Figure 4(i)** presents the results of this calculation for the three-grain types as the function of moisture content. It could be observed that *D* increased with moisture content in all three-

grain types. Nyorere and Uguru (2018) reported the same phenomenon for gmelina seeds and Fadeyibi *et al.* (2021) for miracle berry fruit. Short-bold were also found to have the highest value of *D* while long-medium and very long-slender grains were almost the same. Short-bold grain was the thickest among the grain types tested.

Therefore, when it was compressed normally to the thickness of the grain, the availability of the distance in the vertical direction for the cells to move in the internal of the grain would be more available, this probably caused the deformation to be the largest. Bamrungwong *et al.* (1987) reported that short-bold grain had larger deformation than long-slender grain at the same moisture content. Shitanda *et al.* (2002) also reported that short rough rice grain (*Akitakomachi*) had larger deformation than long rice grain (*LD201* and *Delta*). Statistical analysis showed that grain type, moisture content, and the interaction between these two factors significantly affected *D* values (p<0.05).

The mean comparison resulted that *D* for long-medium and very long slender grains were not significantly different, however, they differed with short-bold grains (**Tables 4** and **5**). The value of *D* for very long-slender grains tended to increase linearly with moisture content, while shot-bold and long-medium grains showed a non-linear pattern with increases in moisture content. For this reason, the relationship of *D* with the moisture content for short-bold and long-medium grains was determined as a polynomial equation (**Table 6**). A similar phenomenon was reported by Altuntas and Yildiz (2007) for faba bean and Resende *et al.* (2013) for milled rice.

5. CONCLUSION

The moisture content, grain type, and the interaction of these two factors had a significant influence on most parameters of the mechanical properties of white rice (p<0.05). The values of R_1, R_1', φ, *a*, *b*, *Ae*, and

D increased while ϑ, F, and S_{max} decreased with the increase in moisture contents for the three-grain types. In general, the relationship between the mechanical parameters of white rice and moisture content could be expressed by a linear equation, except for R_1' for very long-slender grain (*Basmati*), Ae and D for short-bold grain (*Koshihikari*) and medium-length grain (*IR 64*) which were better expressed in quadratic polynomial equations. The equation for determining ϑ based on the value of φ showed a good agreement with the commonly suggested ϑ values.

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7. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the data and the paper are free of plagiarism.

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