Journal of Stored Products Research 68 (2016) 19–24

Contents lists available at ScienceDirect

Journal of Stored Products Research

journal homepage: www.elsevier.com/locate/jspr

The effect of storage pressure on the mechanical properties of paddy grains

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ARTICLE INFO

Article history:
Received 4 December 2014
Received in revised form
1 February 2016
Accepted 22 March 2016
Available online 10 April 2016

Keywords:
Storage pressure
Storage time
Mechanical properties
Paddy grains

ABSTRACT

To investigate the effect of storage pressure and storage time on the mechanical properties of paddy grains, an experimental study was carried out to determine the mechanical properties of paddy grains compressed at minor axis orientation using the Texture Analyzer. The paddy grains were stored under different pressures and for different time. The results showed that as the storage pressure increased from 0 to 300 kPa, the rupture force of paddy grains stored for 60 days decreased from 81.58 to 73.78 N, the rupture energy from 8.10 to 6.27 mJ, the rupture strain from 0.1392 to 0.1168, the apparent contact modulus of elasticity from 171.32 to 57.68 MPa and the maximum contact stress from 40.84 to 19.11 MPa. All of the mechanical properties of the paddy grains exhibited a linear relationship with storage pressure. As for the paddy grains stored under the pressures of 77, 100, 139, 200 kPa, as the storage time increased from 0 to 60 days, the rupture force of the paddy grains decreased from 81.58 to 79.58 N, 81.58 to 79.12 N, 81.58 to 78.21 N and 81.58 to 76.96 N; the rupture energy decreased from 8.10 to 7.55 mJ, 8.10 to 7.35 mJ, 8.10 to 7.08 mJ and 8.10 to 6.85 mJ; the rupture strain decreased from 0.1392 to 0.1309, 0.1392 to 0.1283, 0.1392 to 0.1257 and 0.1392 to 0.1213. The apparent contact modulus of elasticity decreased from 171.32 to 135.97 MPa, 171.32 to 121.77 MPa, 171.32 to 110.59 MPa and 171.32 to 83.32 MPa; the maximum contact stress decreased from 41.16 to 35.00 MPa, 41.16 to 32.45 MPa, 41.16 to 30.32 MPa and 41.16 to 14.97 MPa, respectively. The results revealed that both storage pressure and storage time have a significant effect on the mechanical properties of paddy grains.

1. Introduction

Rice provides energy, vitamins, mineral elements and rare amino acids to human beings. It is the staple food sustaining two-thirds of the world's population (Zhou et al., 2002). In China, paddy is widely cultivated on an area of about 3×10^7 ha with an annual production of about 2.0×10^8 tons (Sun, 2013). Because of the vast territory and the complex climatic conditions in the world, safe storage of a great amount of paddy is of great significance.

During the period of storage, paddy grains are suffering from compressive loading. If the grain pile in the silo is high, the grain at the bottom is under great pressure. If the pressure exceeds the rupture force of the paddy grains, it will cause the paddy grains to crack or break and make them more susceptible to be attacked by microorganisms (Bagheri and Dehpour, 2011). Although some storage pressures are not big enough to make the grain rupture, they damage grains in the interior, so their elasticity, the ability of anti-deformation and anti-rupture are reduced. The breakage or damage of paddy grains does adversely affect seed germination, storage ability and cooking quality (Li et al., 1999). Meanwhile, the longer the storage time of the paddy is, the greater the structure damage of the grains will be. Therefore, it is meaningful to investigate the effects of storage pressure and storage time on the structure of paddy grains.

Studies on mechanical properties of food grains began in the 1960s. Prasad and Gupta (1973) carried out a study on the behavior of paddy grains under quasi-static compressive loading. It was reported that the maximum compressive strength of paddy grains decreased from 160.7 to 40.6 N at a moisture content from 12 to 24% d.b. The modulus of toughness varied from 3.96 to 30.87 mJ and there was a maximum between moisture contents of 14–16% d.b. Altuntas and Yildiz (2007) reported that the rupture force values of Z-axes for chick pea seeds decreased from 551.43 to 548.75 N as the

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http://dx.doi.org/10.1016/j.jspr.2016.03.003
0022-474X/

Nomenclature

a	semi-major axis of the contact area between the compression tool and the specimen(m)
A	cross sectional area of the cylindrical cell (m^2)
b	semi-minor axis of the contact area between the compression tool and the specimen(m)
D	deformation (m)
E	apparent contact modulus of elasticity (MPa)
E_R	rupture energy (mJ)
F	Applied force (N)
F_R	rupture force (N)
K, m, n and $\cos\theta$	constants
p_0	top vertical compressive stress (kPa)
p_h	lateral compressive stress (kPa)
p_v	vertical compressive stress (kPa)
R	maximum radius of curvature at the point of contact of the sample (m)
R'	minimum radius of curvature at the point of contact of the sample (m)
S_{max}	maximum contact stress (MPa)
X	major diameter (mm)
Y	intermediate diameter (mm)
Z	minor diameter (mm)
ε	rupture strain
ρ	bulk density (kg/m^3)
μ	Poisson's ratio of the sample
μ'	friction coefficient
φ	internal friction angle (°)

moisture content increased from 9.89% to 25.08%. Sadeghi et al. (2010) determined the physical and mechanical properties of two rough rice varieties, Sorkheh and Sazandegi, at three moisture content levels. In their study, the compression tests were conducted to determine the average fracture force, fracture energy, modulus of elasticity, and toughness. In contrary to the moisture content at the tested range, variety had a significant effect on the mechanical properties of rough rice. Zareiforoush et al. (2010) measured fracture resistance of paddy grains, in terms of average grain rupture force and energy absorbed in horizontal and vertical orientations at two quasi-static compressive loading rates of 5 and 10 mm/min. They found that different compressive orientations also had an effect on the mechanical properties of paddy grains. As the loading rate increased from 5 to 10 mm/min, the rupture force and rupture energy for the grain decreased from 125.69 to 117.38 N and 33.51 to 29.94 N, from 42.70 to 36.80 mJ and 30.85 to 24.59 mJ, at horizontal and vertical orientations, respectively.

Most studies conducted so far on paddy grains have been focused on the effect of varieties, moisture content and loading rate on the mechanical properties. No detailed study concerning the effect of storage pressure and storage time on the mechanical properties of paddy grains was published so far. Thus, in this study, the paddy grains were stored in a cylindrical cell with top load to simulate the grains in silos. The goal of this study was to investigate the effect of storage pressure and storage time on the rupture force, the rupture energy, the rupture strain, the apparent contact modulus of elasticity and the maximum contact stress of paddy grains.

2. Materials and methods

The paddy used in the experiment was produced in Nanjing, China. This paddy variety, Nanjing 5055, is cultivated widely in Yangtze River region. The mean values of major diameter (X), intermediate diameter (Y) and minor diameter (Z) of the paddy grains were 6.8178 mm, 3.4369 mm and 2.3038 mm, respectively.

The paddy grains were manually cleaned to remove the broken and immature grains. The initial moisture content of the paddy grains was determined using a standard oven-drying method by drying triplicate 10 g samples at 130 °C for 19 h (ASAE Standards, 2001b).

2.1. Storage of paddy grains under different pressures

The LHT-1 rebound modulus tester (Nanjing Soil Instruments Co., Ltd, China) that was used to store paddy consisted of a displacement recorder, a cylindrical cell, a lever, a steel frame and dead weights (Fig. 1). The cylindrical cell of rebound modulus tester was filled with the samples and gently tapped, and then a top cover was added. A vertical pressure was applied to the top surface of the paddy grains through a hanging basket. The desired top pressures (50, 100, 150, 200, 250, 300 kPa) were obtained by adding dead weight in the hanging basket. Six tests of storage of paddy were carried out in the cylindrical cell of rebound modulus testers under top pressures 50, 100, 150, 200, 250, 300 kPa respectively for 60 days. Two tests of storage of paddy were carried out in the cylindrical cell of rebound modulus testers under top pressures 100, 200 kPa respectively for 20 days. The paddy grains had been kept at the temperature of 22 °C. During the storage period, the settlement of the paddy which varied with time was recorded by the displacement recorder.

During the test, the samples suffered from the above vertical stress σ_1, the below vertical stress σ_3, and lateral stress σ_2. Because of the friction resistance of the cylinder wall, the stress acting on the paddy grains in different depth is different.

Taking a small circular thin layer in cylindrical samples, the forces on a thin layer of paddy grains with the depth of y were analyzed as shown in Fig. 2. In this schematic diagram, R is the radius of the cylindrical cell; H is the height of the paddy grains in the cell; μ is the coefficient of friction between the cell wall and the paddy grains; φ is the internal friction angle of the paddy grains.

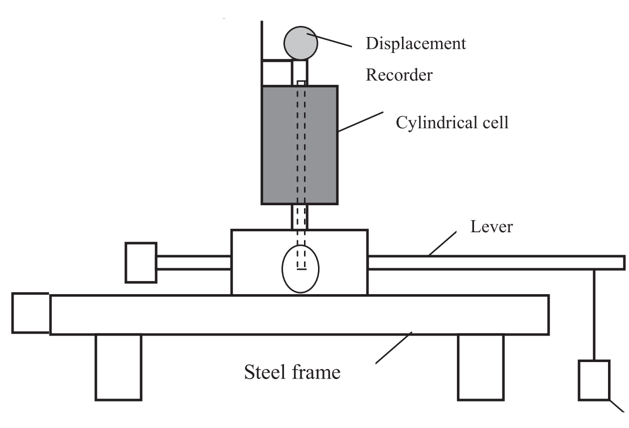

Fig. 1. Schematic illustration of LHT-1 rebound modulus tester.