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Effect of loading rate on mechanical properties of rice (*Oryza sativa* L.) straw

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Abstract

This research was conducted to evaluate the effect of loading rate and internode position on the mechanical properties of rice straw in terms of shear strength, shearing energy, bending strength and Young's modulus. All experiments were conducted at the Department of Agricultural Machinery Engineering, Faculty of Agricultural Engineering and Technology, University of Tehran, Karaj, Iran, in October 2009. The properties were determined at three loading rates: 5, 10 and 15 mm/min and three internodes: the first, second and third internodes. The results showed that the loading rate had only effect on the bending strength. Furthermore, the internode position had significant effect on the shear strength, shearing energy and Young's modulus, and did not have any significant effect on the bending strength. The average shear strength was obtained as 12.18 MPa varying from 8.45 to 20.22 MPa, while the average shearing energy was calculated as 191.34 mJ ranging from 101.31 to 256.02 mJ. The average bending strength was obtained as 7.98 MPa varying from 6.70 to 9.81 MPa, while the average Young's modulus was calculated as 0.66 GPa ranging from 0.21 to 1.38 GPa. The information on the engineering properties of rice straw can be useful for designing the equipment used for harvesting, threshing, and processing.

Keywords: Rice (*Oryza sativa* L.); Shear strength; Shearing energy; Bending strength; Young's modulus

Introduction

Rice (*Oryza sativa* L.) is among the oldest cultivated crops and ranks as the most widely grown food grain crop, serving as the staple food for about half the world's population. In Iran, rice is widely cultivated on an area of about 6.15×10^3 ha with an annual production of about 3.0×10^6 ton (FAO, 2007). Several million tones of straws are produced from this crop annually. These straws usually serve as a feed for animals and sometimes are incorporated into the plowed layer or used as mulch. To attain this purpose, straw must be processed after harvesting. It is necessary to know mechanical properties of rice straw, for selecting design and operational parameters of equipment relating to harvesting, threshing, and processing. Several studies have been conducted in recent years to determine mechanical properties of plants such as: Chen *et al*. (2004) on hemp stems, İnce *et al*. (2005) on sunflower stalks, Nazari Galedar *et al*. (2008) on alfalfa stems, Tavakoli *et al*. (2009b) on barely straw and Tavakoli *et al*. (2009a) on wheat straw. There is no published work relating to the effect of loading rate on mechanical properties of rice straw. Therefore, the objective of this study is to determine the effect of loading rate on mechanical properties, namely, shear strength, shearing energy, bending strength and Young's modulus of rice straw.

Materials and methods

This study was carried out at the Department of Agricultural Machinery Engineering, Faculty of Agricultural Engineering and Technology, University of Tehran, Karaj, Iran, in October 2009. The rice straw (Hashemi variety) used for the present study were from the prevalent varieties of rice in Iran and were obtained from the agronomy farm of the Rice Research Institute, Rasht, Iran, in October 2009. The straws were collected at harvesting time and their internodes were separated according to their position down from the ear (Fig. 1). Leaf blades and sheaths were removed prior to any treatment or measurement (Annoussamy *et al*., 2000).

To determine the average moisture content of the rice straws, the specimens were weighed and oven-dried at 103°C for 24 h (ASAE, 2006) and then weighed. The average moisture content of the specimens was 71.6% wet basis. Three internodes of the rice straw, namely, the first, second and third internodes, were studied in this study (Fig. 1). The fourth and the other lower stem internodes from the ear were not considered because these internodes are usually left on the field. Each internode was described by measuring its length (to the nearest 1 mm), its major and

Table 1. Shearing characteristics of rice straw at different loading rates and internode positions

Loading rate (mm/min)	Internode position*					
	Shear strength (MPa)			Shearing energy (mJ)		
	IN1	IN2	IN3	IN1	IN2	IN3
5	16.11 $_b$	8.58 $_c$	8.45 $_c$	101.31 $_c$	180.28 $_b$	239.51 $_a$
10	20.22 $_a$	10.2 $_c$	8.81 $_c$	122.76 $_c$	228.18 $_{ab}$	236.06 $_a$
15	19.13 $_a$	9.34 $_c$	8.84 $_c$	118.78 $_c$	239.14 $_a$	256.02 $_a$

* Mean values with common index are not significantly different (P>0.05) according to Duncan's multiple range test. IN1, IN2, and IN3: the first, second, and third internodes, respectively

minor diameters and thickness of the elliptical wall (to the nearest 1 µm) using a digital caliper (Mitutoyo, Japan).

Experimental procedure

The mechanical properties of rice straw were assessed using a shearing test similar to those described by İnce *et al.* (2005), Nazari Galedar *et al*. (2008) and Tavakoli *et al.* (2009b) (Fig. 2a) and a three-point bending test similar to those described by Annoussamy *et al*. (2000), Nazari Galedar *et al*. (2008) and Tavakoli *et al*. (2009b) (Fig. 2b). All measurements were made using a proprietary tension/compression testing machine (Instron Universal Testing Machine /SMT-5, SANTAM Company, Tehran, Iran, 2007).

Shearing test

The shear strength was measured in double shear using a shear box (Fig. 2a) consisting essentially of two fixed parallel hardened steel plates 6 mm apart, between which a third plate can slide freely in a close sliding fit. A series of holes with different diameters ranging from 1.5 to 5 mm were drilled through the plates to accommodate internodes of differing diameters. Shear force was applied to the straw specimens by mounting the shear box in the tension/compression testing machine. The sliding plate was loaded at three loading rate of 5, 10 and 15 mm min^{-1} and, as for the shear test, the applied force was measured by a strain-gauge load cell and a force-time record obtained up to the specimen failure. The shear failure stress (or ultimate shear strength), τ_s, of the specimen was calculated from the following equation (Tavakoli *et al*., 2009b):

(1) $$\tau_s = \frac{F_s}{2A}$$

where: τ_s is the shear strength (MPa), F_s is the shear force at failure (N) and A is the wall area of the specimen at the failure cross-section (mm^2). The shearing energy, E_s, was calculated by integrating the area under curves of shear force and displacement (Chattopadhyay and Pandey, 1999; Chen *et al*., 2004; Nazari Galedar *et al*., 2008) using a standard computer program (ver. 5, SMT Machine Linker, SANTAM Company, Tehran, Iran, 2007). An example of the shear force versus displacement curves is shown in Fig 3.

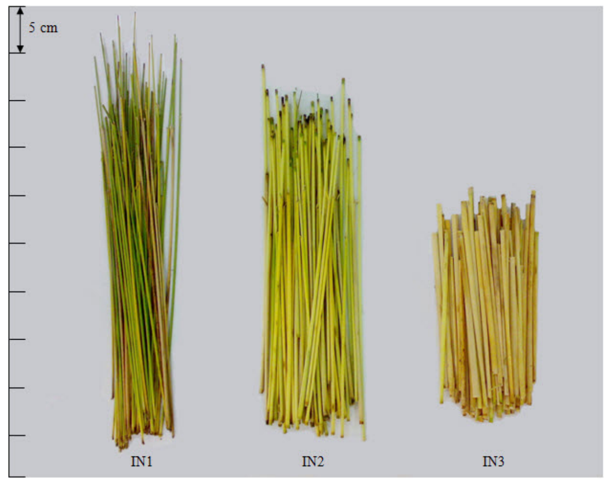

Fig 1. Rice straw internodes (Hashemi variety); IN1, IN2, and IN3: The first, second, and third internodes, respectively

Bending test

To determine Young's modulus and also maximum bending strength, the specimens were arranged with the major axis of the cross-section in the horizontal plane and placed on two rounded metal supports 50 mm apart and then loaded midway between the supports with a blade driven by the movable supports (Tavakoli *et al*., 2009b). The loading rates were 5, 10 and 15 mm min^{-1} and the applied force was measured by a strain-gauge load cell and a force-time record obtained up to the failure of the specimen. Most specimens were slightly elliptical in cross-section and second moment of area in bending about a major axis (I_b) was calculated as (Gere and Timoshenko, 1997):

(2) $$I_b = \frac{\pi}{4}\left[ab^3 - (a-t)(b-t)^3\right]$$

where: I_b is the second moment of area (mm^4), a is the semi-major axis of the cross–section (mm), b is the semi-minor axis of the cross-section (mm) and t is the mean wall thickness (mm). The Young's modulus, E, was calculated from the following expression for a simply supported beam located at its centre (Gere and Timoshenko, 1997):

Table 2. Bending characteristics of rice straw at different loading rates and internode positions

Loading rate (mm/min)	Internode position*					
	Bending strength (MPa)			Young's modulus (GPa)		
	IN1	IN2	IN3	IN1	IN2	IN3
5	9.16 ab	6.70 c	7.04 c	1.38 a	0.44 b	0.21 c
10	8.29 bc	8.71 abc	9.81 a	1.21 a	0.50 b	0.35 bc
15	7.90 c	7.18 c	7.05 c	1.23 a	0.35 bc	0.28 bc

* Mean values with common index are not significantly different (P>0.05) according to Duncan's multiple range test. IN1, IN2, and IN3: the first, second, and third internodes, respectively.

(3) $$E = \frac{F_b l^3}{48\delta I_b}$$

where: E is the Young's modulus (MPa), F_b is the bending force (N), l is the distance between the two metal supports (mm) and δ is the deflection at the specimen centre (mm). The maximum bending strength, σ_b, is defined by (Gere and Timoshenko, 1997; Crook and Ennos, 1994):

(4) $$\sigma_b = \frac{F_b a l}{4 I_b}$$

where: σ_b is the bending stress (MPa).

Experimental design and statistical analysis

This study was planned as a completely randomized block design. The mechanical properties were determined with five replications in each treatment. Experimental data were analysed using analysis of variance (ANOVA) and the means were compared at the 1% and 5% levels of significance using the Duncan's multiple range tests in SPSS software (ver. 15, SPSS, Inc., Chicago, IL, USA, 2008).

Results and discussion

The variance analysis of the data indicated that the effect of loading rate on the bending strength was significant at 5% probability level, while the effect on the shear strength, shearing energy and Young's modulus was not significant (P>0.05). In addition, the internode position created a significant effect (P<0.01) on the shear strength, shearing energy and Young's modulus. The effect of internode position on the bending strength was not significant (P>0.05). Based on the statistical analysis, the interaction effect of loading rate × internode on the shear strength, shearing energy, bending strength and Young's modulus was not significant (P>0.05). The results obtained are discussed in details as follows.

Shear strength

The mean values of the shear strength at different loading rates and internodes are presented in Table 1. According to

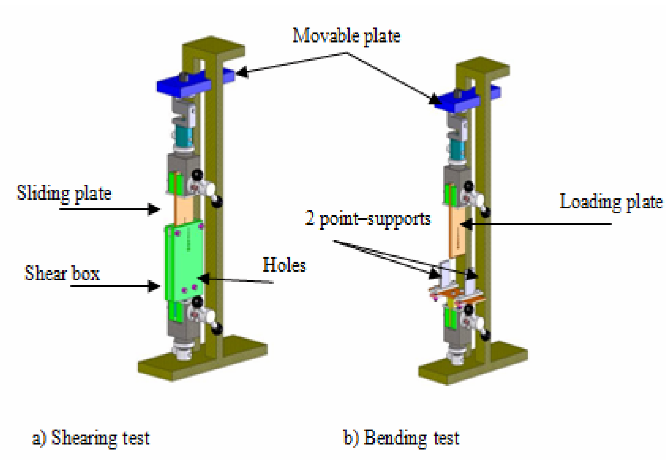

Fig 2. Apparatus used to measure a) shearing, and b) bending strength of rice straw internodes

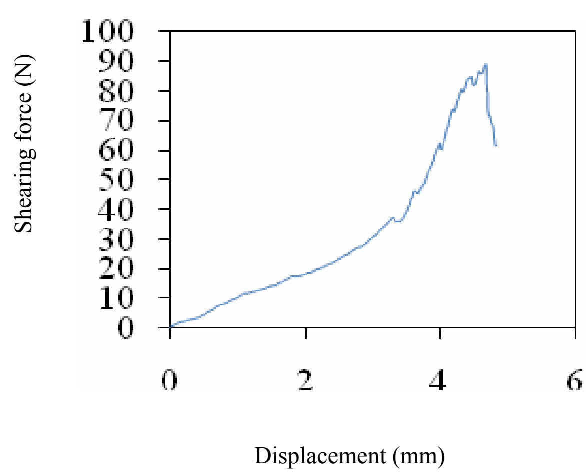

Fig 3. The shearing force versus displacement curve for rice straw (Hashemi variety)

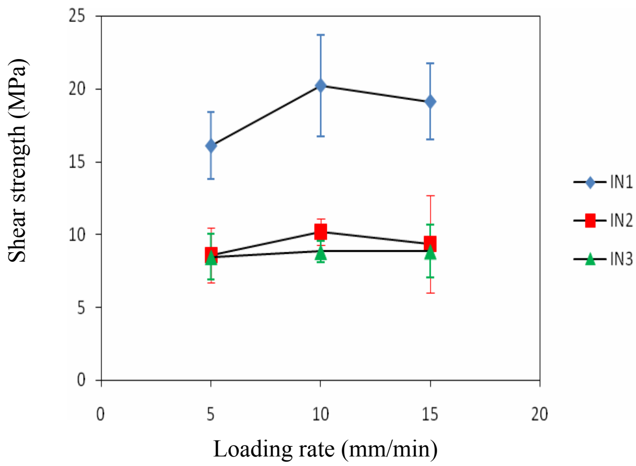

Fig 4. Effect of loading rate and internode position on shear strength of rice straw

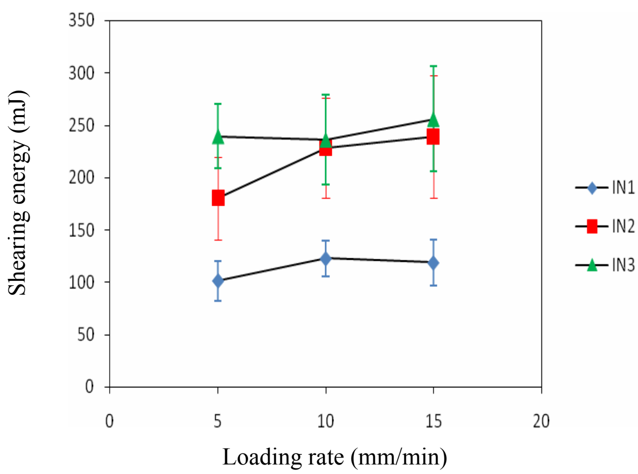

Fig 5. Effect of loading rate and internode position on shearing energy of rice straw

the Duncan's multiple range tests, the loading rate did not have significant effect (P>0.05) on the shear strength of rice straw. Furthermore, the effect of internode position on the shear strength was significant at 1% probability level. The shear strength increased towards the first internode (Fig. 4). The average shear strength was obtained as 12.18 MPa varying from 8.45 to 20.22 MPa. Kushaha *et al*. (1983) reported mean values of shear strength of wheat straw in the range of 7–22 MPa for stem moisture content ranging from 5 to 30% w.b. The effect of moisture content and level of crop on the shear strength of alfalfa stems was studied by Nazari Galedar *et al*. (2008). They reported that the shear strength of alfalfa stems increased from 5.98 to 28.16 MPa at the upper level with the lowest moisture content (10% w.b.) and the lower level with the highest moisture content (80% w.b.), respectively. Tavakoli *et al*. (2009b) determined shear strength of barley straw. They reported that the values of the shear strength were within the ranges 3.90–5.27 MPa, 4.31–5.96 MPa, and 4.49–6.18 MPa for the first, second and third internode positions, respectively. Tavakoli *et al*. (2009a) showed that the shear strength of wheat straw increased towards the third internode position.

Shearing energy

The mean values of the shearing energy at different loading rates and internodes are presented in Table 1. According to the Duncan's multiple range tests, the loading rate did not have significant effect (P>0.05) on the shearing energy of rice straw. In addition, the effect of internode position on the shear strength was significant at 1% probability level. The shearing strength increased towards the third internode (Fig. 5). The shearing energy was higher in the lower internodes, possibly due to the accumulation of more mature fibres in the stem. The effect of stem height on shearing energy was also reported by Nazari Galedar *et al*. (2008) for alfalfa stem and Tavakoli *et al*. (2009b) for barley straw. The average shearing energy was calculated as 191.34 mJ ranging from 101.31 to 256.02 mJ. Based on the reports of McRandal and McNulty (1980) in the case of field grasses, the mean specific shearing energy was 12.0 mJ mm^{-2}. The specific shearing energy of sunflower stalks was determined by İnce *et al*. (2005), who reported the range of 1.99 to 10.08 mJ mm^{-2} for moisture content range of 20 to 80% d.b. Nazari Galedar *et al*. (2008) reported that the values of the shearing energy of alfalfa stem varied from 20.2–73.1 mJ, 64.20–187.60 mJ, and 185.20–345.8 mJ for the upper, middle and lower levels, respectively, at the different moisture contents (in the range of 10 to 80% w.b.).

Bending strength

The bending strength of rice straw at different loading rates and internodes are shown in Table 2. By using Duncan's multiple range tests, the loading rate had significant effect (P<0.05) on the bending strength of rice straw. The values of the bending strength decreased with increasing loading rate for the first internode, while for the second and third internodes, the values at the first increased with increasing loading rate from 5 to 10 mm/min and then decreased (Fig. 6). The effect of internode position on the bending strength was not significant (P>0.05). The average bending strength was obtained as 7.98 MPa varying from 6.70 to 9.81 MPa. The values obtained in the current study for rice straw were lower than that of sorghum stalk (45.65 MPa) at the forage stage, those of alfalfa stems (9.71 to 47.49 MPa) at moisture content range of 10 to 80% w.b., and those of wheat straw (8.92 to 19.31 MPa) at moisture content range of 10.2 to 22.6% w.b. (Chattopadhyay and Pandey, 1999; Nazari Galedar *et al*., 2008; Tavakoli *et al*., 2009a). Furthermore, the values of bending strength for rice straw were close to those of barley straw (6.30 to 8.55 MPa) at moisture content range of 10.8 to 22.5% w.b. (Tavakoli *et al*., 2009b). Therefore, the rice straw is more flexible in comparison with sorghum stalk, alfalfa stem and wheat straw.

Young's modulus

The Young's modulus of rice straw at different loading rates and internodes are shown in Table 2. By using

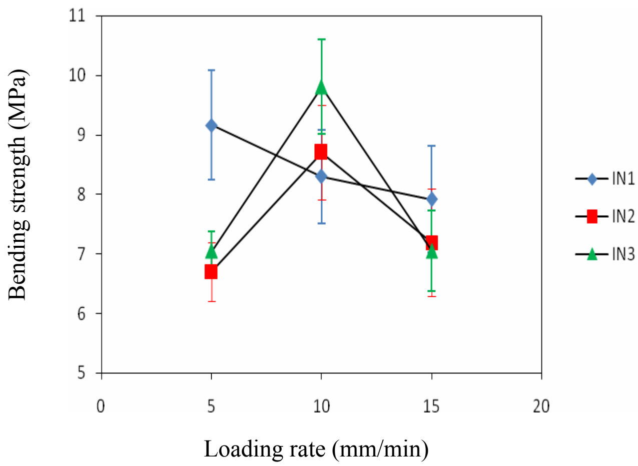

Fig 6. Effect of loading rate and internode position on bending strength of rice straw

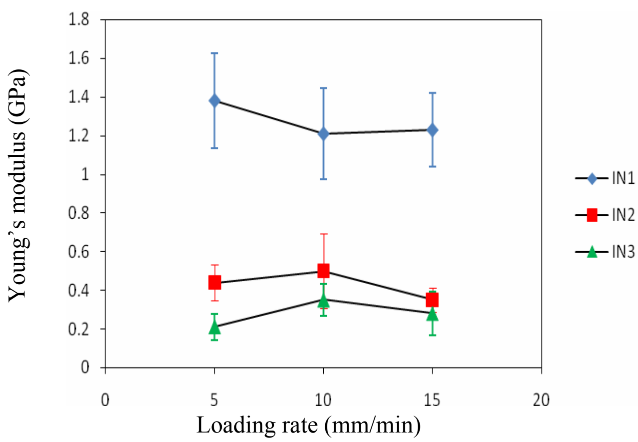

Fig 7. Effect of loading rate and internode position on Young's modulus of rice straw

Duncan's multiple range tests, the loading rate did not have any significant effect (P>0.05) on the Young's modulus of rice straw. Furthermore, the effect of internode position on the Young's modulus was significant at 1% probability level. The Young's modulus decreased towards the third internodes (Fig. 7). Similar decreasing trends were reported by O'Dogherty *et al*. (1995) for wheat straw, Nazari Galedar *et al*. (2008) for alfalfa stems and Tavakoli *et al*. (2009b) for barley straw. The average Young's modulus of rice straw was calculated as 0.66 GPa ranging from 0.21 to 1.38 GPa. The values of the Young's modulus for rice straw were found to be lower than those of wheat straw (4.76 to 6.58 GPa) and those of alfalfa stems (0.63 to 4.60 GPa) (O'Dogherty *et al*., 1995; Nazari Galedar *et al*., 2008).

Conclusions

The following conclusions were drawn from the investigation of the effect of loading rate and internode position on the shear strength, shearing energy, bending strength and Young's modulus of rice straw. The loading rate did not have any effect on the shear strength, shearing energy and Young's modulus, while it had effect on the bending strength. The internode position had significant effect on the shear strength, shearing energy and Young's modulus, while it did not have significant effect on the bending strength. The mean values of the shear strength, shearing energy, bending strength and Young's modulus were obtained as 12.18 MPa, 191.34 mJ, 7.98 MPa and 0.66 GPa, respectively. This paper concludes with information on the engineering properties of rice straw which may be useful for designing the equipment used for harvesting, threshing, and processing. It is recommended that other engineering properties such as coefficient of friction, bulk density, tensile strength, rigidity modulus, and Poisson's ratio be measured or calculated to provide fairly comprehensive information on design parameters involved in rice straw harvesting and processing equipment.

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