Int. Agrophysics, 2009, 23, 175-181

INTERNATIONAL
Agrophysics
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Physical and mechanical properties of wheat straw as influenced by moisture content

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Received September 28, 2008; accepted January 14, 2009

A b s t r a c t. The objective of this research was to determine the effects of moisture content and internode position on some physical and mechanical properties of wheat straw. The experiments were conducted at four moisture contents of 10.2, 14.3, 18.4, and 22.6% w.b. and at three internode positions down from the ear. Based on the results obtained, the values of the physical properties increased with increasing moisture content. The physical properties also increased towards the third internode position. For all the physical properties studied, the values of the first internode position had significant differences with those of the other two internode positions. Moreover, for the moisture contents studied in this research, the values of shear strength were within the ranges 6.81-10.78, 7.02-11.49, and 7.12-11.78 MPa for the first, second and third internode positions, respectively. The maximum specific shearing energy was 36.26 mJ mm^{-2}, which occurred at the third internode position with the moisture content of 22.6% w.b. The bending strength and Young's modulus decreased with increase in the moisture content. Their values also decreased towards the third internode position.

K e y w o r d s: wheat, straw, Young's modulus, shear strength, shearing energy

INTRODUCTION

Based on FAO information, wheat is the second most produced food among the in the world. In Iran, wheat is widely cultivated on approximately 6 941 286 ha with an annual production of 14×10^6 t (FAO, 2007). Wheat straw is one of the most abundant field crop residues in Iran because of its high cultivated area. The straw usually serves as feed for animals and sometimes is incorporated into the ploughed layer or used as mulch. For these purposes, straw must be processed *eg* by threshing, handling *etc*. after harvesting. In order to design equipments for harvesting, threshing, handling and also other required processing, it is necessary to obtain the physical and mechanical properties of wheat straw.

Most studies on the mechanical properties of plants have been carried out during their growth using failure criteria (force, stress and energy) or their Young's modulus and the modulus of rigidity. Studies have focused on plant anatomy, lodging processes, harvest optimisation, animal nutrition, industrial applications and the decomposition of wheat straw in soil (Announssamy *et al*., 2000; Skubisz *et al*., 2007). The properties of cellular material that are important in cutting are compression, tension, bending, shearing, density and friction. These properties depend on the species, variety, stalk diameter, maturity, moisture content and cellular structure (Persson, 1987). These physical properties are also different at different heights of the plant stalk (Nazari Galedar *et al.,* 2008b). Methods and procedures for determining most of mechanical and rheological properties of agricultural products were described by Mohsenin (1986).

Dernedde (1970) used a shear box method to measure shear strength of different varieties of tested forage materials singly. In two series of experiments he found ranges of 25-88 and 59-128 MPa, with maximum at moisture contents of 20 and 35% w.b. for the two sets of data. O'Dogherty *et al*. (1995) measured the shear strength of six varieties of wheat straw and found mean values in the range of 5.4-8.5 MPa. Shinners *et al*. (1987) found that longitudinal shearing of alfalfa stems required less than 1/10 of the energy to shear alfalfa transversely. McRandal and McNulty (1980) conducted shearing experiments on field grasses and found that the mean shearing stress was 16 MPa and the mean shearing energy was 12.0 mJ mm^{-2}. O'Dogherty *et al*. (1995) showed that the Young's modulus for wheat straw varied between 4.76 and 6.58 GPa. Chattopadhyay and Pandey (1999) found that the bending stress for sorghum stalks at the seed stage and forage stage were 40.53 and 45.65 MPa, respectively.

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Similar works have been conducted in recent years: Skubisz (2001) on rape stem, Skubisz (2002) on pea stem, Chen *et al*. (2004) on hemp stem, İnce *et al*. (2005) on sunflower stalk and Nazari Galedar *et al*. (2008a) on alfalfa stems.

It seems that there is not much published work relating to effects of moisture content and internode position on physical and mechanical properties of wheat straw. Therefore, the objective of this study was to investigate the effects of moisture content and internode position on some physical properties including major and minor diameters, thickness, cross-section area, second moment of area and mass per unit length, and mechanical properties, namely, shear strength, specific shearing energy, bending strength and Young's modulus of wheat straw.

MATERIALS AND METHODS

The wheat variety used in the current research, Alvand, is one of the prevalent varieties in Iran which was prepared at the agronomy farm of the Seed and Seedling Research Institute, Karaj, Iran. The straw specimens were collected at harvesting period and their internodes were separated according to their position down from the ear (Fig. 1) (Annoussamy *et al*. 2000). Leaf blades and sheaths were removed prior to any treatment or measurement. To determine the average moisture content of the straws, the specimens were weighed and then oven-dried at 103°C for 24 h (ASAE, 2006) and finally reweighed. The initial moisture content of the specimens was 10.2% w.b. To attain desired moisture levels, the specimens were rewetted by adding a precalculated mass of water using the following relationship (Shaw and Tabil, 2006):

$$m_w = \frac{m_i\left(M_{wf} - M_{wi}\right)}{1 - M_{wf}}, \tag{1}$$

where: m_w is mass of water added to sample (g), m_i is initial mass of sample (g), M_{wf} is final desired moisture content of sample (% w.b.) and M_{wi} is initial moisture content of sample (% w.b.).

The experiments were conducted at moisture levels of 10.2, 14.3, 18.4, and 22.6% w.b. Three internodes of wheat stem, namely, first, second and third internodes were studied in this research (Fig. 1). The fourth and other stem internodes from the ear were not considered because these internodes are usually left on the field. Each internode was described by measuring its mass (to the nearest 0.1 mg), its length (to the nearest 1 mm), its major and minor diameter and thickness of the elliptical wall to the nearest 1 µm using a digital caliper.

The mechanical properties of the wheat straw were assessed using a shearing test similar to those described by O'Dogherty *et al*. (1995), İnce *et al*. (2005) and Nazari Galedar *et al*. (2008a) (Fig. 2a), and a three-point bending test similar to those described by Crook and Ennos (1994), Annoussamy *et al*. (2000) and Nazari Galedar *et al*. (2008a) (Fig. 2b). The measurements were made using a proprietary tension/compression testing machine (Instron UTM/SMT-5, SANTAM Company, Tehran, Iran).

The shear strength was measured in double shear using a shear box (Fig. 2a) consisting essentially of two fixed parallel hardened steel plates spaced 6 mm apart, between which a third plate can slide freely in a close sliding fit. A series of holes with 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 a rate of 10 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:

$$\tau_s = \frac{F_s}{2A} \tag{2}$$

where: 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).

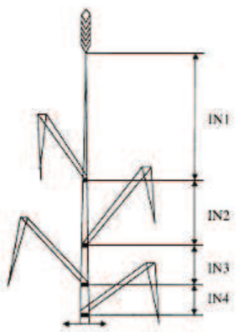

Fig. 1. Diagram of straw identifying internodes.

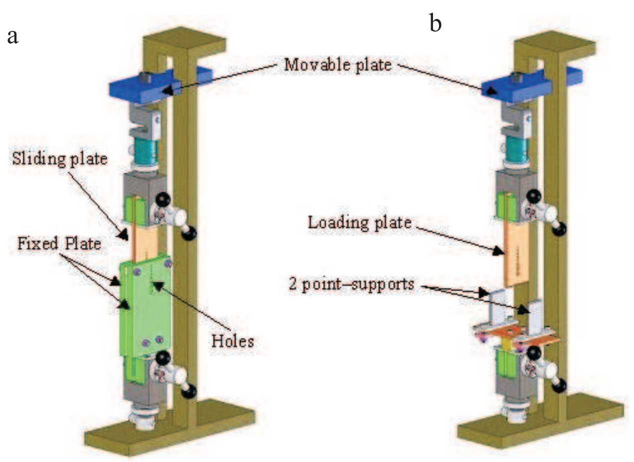

Fig. 2. Apparatus for the measurement of: a – shearing, b – bending strength of straw internodes.

The shearing energy was calculated by integrating the area under shear force and displacement curves (Chattopadhyay and Pandey, 1999; Chen *et al*., 2004; Nazari Galedar *et al*., 2008a) using a standard computer program (version 5, SMT Machine Linker, SANTAM Company, Tehran, Iran). A sample of the shear force versus displacement curves is shown in Fig. 3.

The specific shearing energy, E_{sc}, was found by the below equation:

$$E_{sc} = \frac{E_s}{A}, \tag{3}$$

where: E_s is the shearing energy (mJ).

To determine Young's modulus and bending strength, the specimens were arranged with the major axis of the cross-section in the horizontal plane and placed on two rounded metallic supports 50 mm apart and then loaded midway between the supports with a blade driven by the movable supports. The loading rate was 10 mm min^{-1} and the force applied 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, therefore, the second moment of area in bending about a major axis, I_b, was calculated as (Gere and Timoshenko, 1997):

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

where: a is the semi-major axis of the cross-section, b is the semi-minor axis of the cross-section and t is the mean wall thickness (all in mm).

The Young's modulus, E, was calculated from the following expression for a simply supported beam loaded at its centre (Gere and Timoshenko, 1997):

$$E = \frac{F_b l^3}{48\delta I_b}, \tag{5}$$

where: F_b is the bending force (N), l is the distance between the two metal supports (mm), δ is the deflection at the specimen centre (mm) and I_b is the second moment of area (mm^4).

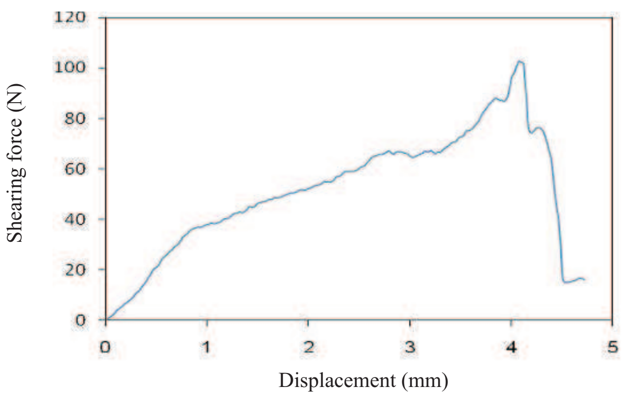

Fig. 3. Shearing force versus displacement curve for wheat straw.

The bending strength, σ_b, is defined by the following equation (Gere and Timoshenko, 1997; Crook and Ennos, 1994):

$$\sigma_b = \frac{F_b a l}{4 I_b}. \tag{6}$$

This study was planned as a completely randomized block design. The mechanical and physical properties were determined with five and ten replications for each treatment, respectively. Experimental data were analysed using analysis of variance (ANOVA) and the means were separated at the 5% probability level applying Duncan's multiple range tests in SPSS 15 software.

RESULTS AND DISCUSSION

The mean values for the physical properties of wheat straw are presented in Table 1. The moisture content had little effect on the physical properties of wheat straw. With increase in the moisture content, the physical properties generally increased. The effect of moisture content on the stem major and minor diameters, thickness, wall cross-sectional area and second moment of area was not significant at 5% probability level. The mass per unit length was found to be significantly lower ($P<0.05$) for the lowest moisture content with a mean value of 1.63 g m^{-1}. This compares with a mean value of 1.88 g m^{-1} for straw moisture contents in the range of 14.3 to 22.6% w.b. The physical properties also increased towards the third internode position. For all physical properties studied the values of the first internode position had significant differences ($P<0.05$) with the other two internode positions. Similar trends of increasing for stem diameter, wall cross-sectional area and second moment of area towards the lower level of crop were reported by O'Dogherty *et al.* (1995) for wheat straw and Nazari Galedar *et al.* (2008a) for alfalfa stem.

The mean values for shear strength of wheat straw at different moisture contents and internode positions are presented in Table 1. As shown in Fig. 4a the shear strength increased exponentially with an increase in moisture content for all internode positions. Similar results were reported by most previous researchers (McRandal and McNulty, 1980; Annoussamy *et al*., 2000; Nazari Galedar *et al*., 2008a). The moisture content had a significant effect on the shear strength at 5% probability level. According to the Duncan multiple range tests, the values were completely different for the distinct moisture contents. The shear strength also increased towards the third internode position. The effect of internode position and interaction effect of moisture content × internode position on the shear strength were not significant ($P>0.05$). The equations representing the relationship between shear strength and moisture content for each internode position and their coefficients of determination (R^2) are presented in Table 2.

T a b l e 1. Physical and mechanical properties of wheat internodes (IN1, IN2, IN3) as a function of moisture content (10 observations)

Parameters	Moisture content (% w.b.)											
	10.24			14.20			18.42			22.61		
	IN1	IN2	IN3	IN1	IN2	IN3	IN1	IN2	IN3	IN1	IN2	IN3
d_1 (mm)	3.46b (0.37)*	4.14a (0.42)	4.15a (0.40)	3.50b (0.27)	4.15a (0.29)	4.16a (0.18)	3.51b (0.30)	4.20a (0.36)	4.19a (0.24)	3.54b (0.20)	4.24a (0.23)	4.21a (0.18)
d_2 (mm)	3.01b (0.26)	3.81a (0.31)	3.73a (0.45)	3.03b (0.28)	3.76a (0.28)	3.82a (0.22)	3.11b (0.35)	3.88a (0.37)	3.91a (0.15)	3.16b (0.21)	3.86a (0.24)	3.91a (0.15)
t (mm)	0.42bcd (0.06)	0.45abcd (0.05)	0.50ab (0.08)	0.40d (0.04)	0.47abcd (0.09)	0.53a (0.15)	0.41cd (0.05)	0.45abcd (0.06)	0.47abcd (0.10)	0.44bcd (0.06)	0.46abcd (0.04)	0.49abc (0.10)
A (mm^2)	3.79b (0.81)	5.08a (0.96)	5.40a (1.18)	3.60b (0.34)	5.23a (1.24)	5.64a (1.29)	3.74b (0.63)	5.14a (1.05)	5.27a (1.13)	4.01b (0.64)	5.20a (0.65)	5.47a (1.02)
I_b (mm^4)	3.50b (1.38)	7.69a (2.74)	7.80a (3.49)	3.36b (0.84)	7.54a (2.75)	7.96a (1.74)	3.75b (1.25)	8.17a (3.21)	8.10a (1.72)	3.99b (1.13)	7.98a (2.04)	8.38a (1.69)
ML (g m^{-1})	1.27e (0.23)	1.75bcd (0.43)	1.86abc (0.32)	1.26e (0.20)	2.14ab (0.61)	2.07ab (0.36)	1.47ed (0.42)	2.04ab (0.38)	2.09ab (0.36)	1.59cde (0.32)	2.12ab (0.41)	2.17a (0.39)
τ_s (MPa)	6.81f (1.46)*	7.02ef (1.03)	7.12def (1.42)	8.49cdef (0.91)	8.57cde (0.61)	8.80cd (0.98)	9.01bc (0.93)	10.07abc (1.34)	10.57ab (1.22)	10.78a (1.01)	11.49a (1.46)	11.78a (1.79)
E_{sc} (mJ mm^{-2})	21.85i (2.68)	24.25hi (2.41)	25.74gh (2.82)	27.42fg (1.99)	29.67def (1.56)	30.82cde (1.02)	29.14ef (1.34)	32.15bcd (2.06)	33.05bc (1.65)	32.49bcd (2.45)	35.08ab (1.89)	36.26a (2.38)
σ_b (MPa)	19.31a (2.59)	14.95c (0.92)	13.70cd (1.71)	17.01b (1.53)	12.10de (1.24)	11.86e (0.47)	14.54c (1.67)	11.79e (1.23)	11.36e (0.45)	11.11e (0.86)	9.28f (0.81)	8.92f (0.82)
E (GPa)	1.82a (0.45)	1.05cd (0.31)	0.98cde (0.18)	1.73a (0.08)	1.03cd (0.19)	0.87cde (0.28)	1.39b (0.42)	0.87cde (0.29)	0.78de (0.12)	1.14bc (0.22)	0.77de (0.18)	0.65e (0.13)

*Dates in parentheses are standard deviation. a-i – means followed by different letters are significantly different from others in the same line ($P < 0.05$). d_1, d_2 and t – major and minor diameter and thickness of stem, respectively, A – cross-section area of wall, I_b – second moment of area, ML – mass per unit length, τ_s, σ_b – shear and bending strength, respectively, E_{sc} – specific shearing energy, E – Young's modulus.

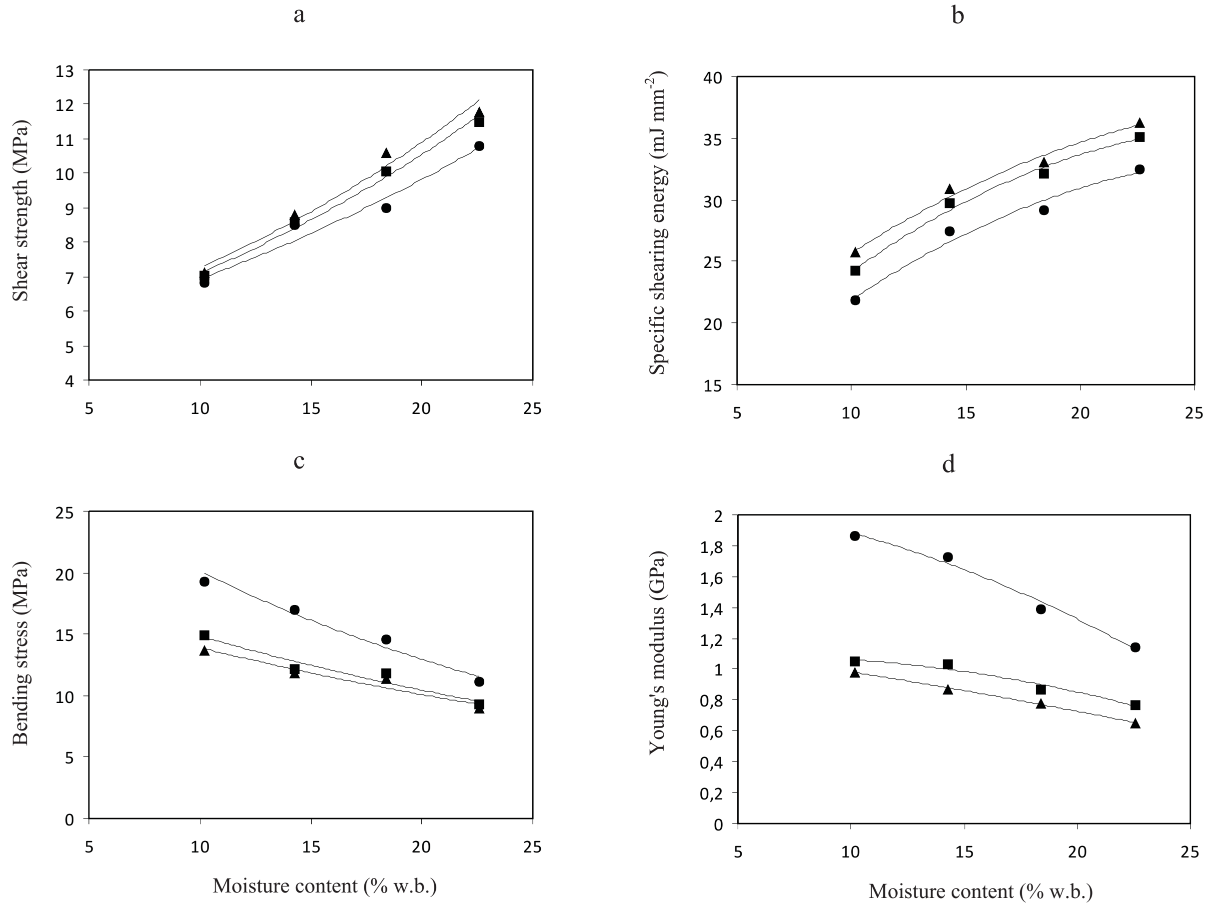

Fig. 4. Variation of: a – shear strength, b specific shearing energy, c – bending strength, and d – Young's modulus with moisture content and internode positions: ● first,■ second and ▲ third.

The specific shearing energy increased with increasing moisture content for all internode positions (Fig. 4b). This effect of moisture content was also reported by Chen *et al.* (2004) for hemp stalk and Nazari Galedar *et al.* (2008a) for alfalfa stem. The values of the specific shearing energy varied from 21.85 to 36.26 mJ mm^{-2} at the first internode with the lowest moisture contents and the third internode with the highest moisture contents, respectively (Table 1). The reason for this difference may be attributed to the viscous damping effect of moisture as reported by Persson (1987). The values of the specific shearing energy were significantly affected by moisture content at the 5% probability level. According to the Duncan multiple range test results, these values were different from each other for the distinct moisture contents. The specific shearing energy also decreased towards the first internode position. Its values varied from 21.85 to 32.49 mJ mm^{-2}, 24.25 to 35.08 mJ mm^{-2} and 25.74 to 36.26 mJ mm^{-2} for the first, second and third internode positions, respectively, at the different moisture contents studied. It was greater at the third internode because of the accumulation of more mature fibres in the stem (İnce *et al.*, 2005). The specific shearing energy at the first internode position was found to be significantly lower ($P<0.05$) than the other two internode positions. The interaction effect of moisture content × internode position on the specific shearing energy was not significant ($P>0.05$). The equations representing relationship between specific shearing energy and moisture content for each internode position and their coefficients of determination (R^2) are presented in Table 2.

As shown in Fig. 4c the bending strength decreased exponentially with increase in moisture content for all internode positions, indicating a reduction in the brittleness of the stem. This result was also reported by İnce *et al.* (2005) for sunflower stalk and Nazari Galedar *et al.* (2008b) for alfalfa stem. Its values decreased from 19.31 to 11.11, 14.95 to 9.28, and 13.70 to 8.92 MPa for the first, second and third internode positions, respectively, as the moisture content increased from 10.2 to 22.6% w.b. (Table 1). The bending strength also decreased towards the third internode position. The moisture content had significant effect ($P<0.05$) on the bending strength. According to the Duncan multiple range tests, its values were different from each

T a b l e 2. Equations representing the relationship between the mechanical properties of wheat straw and moisture content for each internode position

Mechanical properties	IN1	R^2	IN2	R^2	IN3	R^2
τ_s (MPa)	$4.895e^{0.034Mc}$	0.959	$4.77e^{0.039Mc}$	0.990	$4.804e^{0.041Mc}$	0.979
E_{sc} (mJ mm^{-2})	$-0.033Mc^2+1.907Mc+6.134$	0.975	$-0.037Mc^2+2.074Mc+7.157$	0.991	$-0.028Mc^2+1.746Mc+11.06$	0.987
σ_b (MPa)	31.19e-0.04Mc	0.970	$21.14e^{-0.03Mc}$	0.930	$19.21e^{-0.03Mc}$	0.930
E (MPa)	$-0.001Mc^2-0.006Mc+2.113$	0.985	$-0.001Mc^2+0.012Mc+1.048$	0.961	$-0.001Mc^2-0.017Mc+1.184$	0.997

other for the distinct moisture contents. The first internode position had significantly higher values (P<0.05) than the other two internode positions. The interaction effect of moisture content×internode position on the bending strength was not significant (P>0.05). The equations representing the relationship between bending strength and moisture content for each internode position and their coefficients of determination (R^2) are presented in Table 2.

The Young's modulus in bending decreased with increasing in the moisture content for all internode positions (Fig. 4d). Similar trend of decreasing was reported by İnce *et al*. (2005) for sunflower stalk and Nazari Galedar *et al*. (2008b) for alfalfa stem. The range of values was from 0.65 to 1.82 GPa at the third internode with highest moisture contents and the first internode with the lowest moisture contents, respectively (Table 1). The Young's modulus also decreased towards the third internode position. According to the Duncan multiple range tests, the Young's modulus was found to be significantly higher (P<0.05) for the two lowest moisture contents (10.2 and 14.3% w.b.) with a mean value of 1.25 GPa. This is compared with a mean value of 0.93 GPa for other two moisture contents (18.4 and 22.6% w.b.). Also the first internode had significantly higher values (P<0.05) than the other two internode positions. The interaction effect of moisture content × internode position on the Young's modulus was not significant at the 5% probability level. The equations representing the relationship between Young's modulus and moisture content for each internode position and their coefficients of determination (R^2) are presented in Table 2.

CONCLUSIONS

1. An increase in moisture content of straw led to a decrease in the bending strength and Young's modulus and an increase in the shear strength and specific shearing energy.

2. The shear strength, specific shearing energy, bending strength and Young's modulus varied from 6.81 to 11.78 MPa, 21.85 to 36.26 mJ mm^{-2}, 8.92 to 19.31 MPa and 0.65 to 1.82 GPa, respectively.

3. There were a big difference between the highest and the lowest moisture contents in terms of shear strength and specific shearing energy. This result indicates that threshing of wheat straw at lower moisture contents can be recommended to minimise the shearing force and shearing energy requirements.

4. For all moisture contents the Young's modulus and bending strength increased towards the first internode position, while the shear strength and specific shearing energy decreased.

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