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Machanical Engineering

Elixir Mech. Engg. 42 (2012) 6415-6419

ISSN: 2229-712X

Comparison of mechanical properties between two varieties of sugar cane stalks

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ARTICLE INFO

Article history:

Received: 21 November 2011;
Received in revised form:
15 January 2012;
Accepted: 26 January 2012;

Keywords

Sugar cane; Internode,
Shear strength,
Specific shearing energy; Young's modulus.

ABSTRACT

In this paper, some engineering properties of sugar cane stalk are determined. For this purpose, two varieties of sugar cane including L310 and L820 varieties with average moisture contents of 76.4 and 73.8% wet basis, respectively, were used. The experiments were conducted at ten internode positions down from the flower for both varieties. Based on the results obtained, the averages of stalk's diameter, cross-section area and second moment of area of L310 variety were higher than those of L820 variety, while the average of stalk's length of L820 variety was higher than that of L310 variety. The internode position had no significant effect on the shearing and bending properties of both varieties. Furthermore, there was significant difference between the two varieties in the case of Young's modulus, while there was not any difference in the case of shear strength, specific shearing energy and bending strength. The average of Young's modulus of L820 variety was significantly higher than that of L310 variety. The mean values of shear strength, specific shearing energy, bending strength, and Young's modulus of L310 and L820 varieties were obtained as 4.92 and 5.25 MPa, 53.36 and 57.35 mJ mm^{-2}, 9.58 and 9.20 MPa, and 18.81 and 24.50 MPa, respectively.

Introduction

Sugar cane (*Saccharum officinarum* L.), a member of the grass family, is a perennial agricultural crop grown primarily for the juices extracted from its stalks. Raw sugar produced from these juices are later refined into white sugar. As a perennial crop, one planting of sugarcane will generally allow for three to six or more annual harvests before replanting is necessary. In Iran, sugar cane is widely cultivated on an area of about 60378 ha with an annual production of about 3034936 ton (FAO, 2009). The mechanical properties of Sugar cane stalk are essential for the design of equipment and the analysis of the behavior of the product during agricultural process operations such as harvesting, handling, threshing, and processing.

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 decomposition of wheat straw in soil (Annoussamy et al., 2000; Nazari Galedar et al., 2008). The properties of the 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 (Tavakoli et al., 2009). These physical properties are also different at different heights of the plant stalk (İnce et al., 2005). Methods and procedures for determining most mechanical and rheological properties of agricultural products were described by Mohsenin (1986).

Several studies have been conducted to determine mechanical properties of plants in recent years such as: Skubisz (2001) on rape stem, Skubisz (2002) on pea stem, 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. (2009) on wheat straw and Zareiforoush et al. (2010) on rice straw.

There is no published work relating to the physical and mechanical properties of sugar cane stalks. Therefore, the objective of this study is to determine physical properties such as stalk diameter, cross-section area, second moment of area, and internode length, and mechanical properties, namely, shear strength, specific shearing energy, bending strength and Young's modulus of two Iranian sugar cane varieties.

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 August 2010. The sugar cane stalks (L310 and L820 varieties) used for the present study were from the prevalent varieties of sugar cane in Iran and were obtained from the agronomy farm of the agro-industry of Mirza Kouchak Khan, Ahvaz, Iran, in August 2010.

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The stalks were collected at harvesting time and their internodes were separated according to their position down from the flower (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 stalks, the specimens were weighed and oven-dried at 103°C for 72 h and then weighed. The average moisture contents of the specimens were 76.4 and 73.8% wet basis for L310 and L820 varieties, respectively. Ten internodes of the sugar cane stalks, namely, IN1, IN2, IN3, IN4, IN5, IN6, IN7, IN8, IN9 and IN10, were studied in this study (Fig. 1). Each internode was described by measuring its length (to the nearest 1 mm) and its diameter (to the nearest 1 μm) using a digital caliper (Mitutoyo, Japan).

Fig. 1 Sugar cane stalk internodes; IN1, IN2 … and IN10: The first, second … and tenth internodes, respectively.

Experimental procedure

The shearing characteristics of sugar cane stalks were assessed using a shearing test similar to those described by İnce et al. (2005), Nazari Galedar et al. (2008), and Tavakoli et al. (2009) (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. (2009) (Fig. 2b). All measurements were made using a proprietary tension/compression testing machine (Instron Universal Testing Machine /SMT-5, SANTAM Company, Tehran, Iran, 2007).

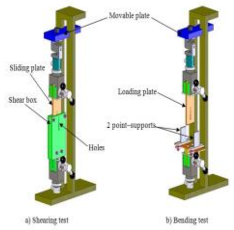

Fig.2. Apparatus used to measure a) shearing, and b) bending strength of sugar cane stalk internodes

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 10 to 30 mm were drilled through the plates to accommodate internodes of differing diameters. Shear force was applied to the stalk 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 (Tavakoli et al., 2009):

$$\tau_s = \frac{F_s}{2A} \quad [1]$$

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 (Chen et al., 2004; Nazari Galedar et al., 2008; Zareiforoush et al., 2010) using a standard computer program (ver. 5, SMT Machine Linker, SANTAM Company, Tehran, Iran, 2007). The curves were used to evaluate: a) the shear strength, obtained by using the maximum recorded force; b) the shearing energy, given by the area under the curves.

The specific shearing energy, E_{sc} was calculated by:

$$E_{sc} = \frac{E_s}{A} \quad [2]$$

where: E_{sc} is the specific shearing energy (mJ mm^{-2}) and E_s is the shearing energy (mJ).

Bending test

To determine Young's modulus and also maximum bending strength, the specimens were arranged 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. The loading rate was 10 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. The specimens were spherical in cross-section and second moment of area about diameter in bending was calculated as (Gere and Timoshenko, 1997):

$$I_d = \frac{\pi}{64} \times d^4 \quad [3]$$

where: I_d is the second moment of area (mm^4), and d is the stalk diameter(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):

$$E = \frac{F_b l^3}{48\delta I_d} \quad [4]$$

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):

$$\sigma_b = \frac{F_b dl}{8I_d} \quad [5]$$

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 and physical properties were determined with five and ten replications in each treatment, respectively. 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 mean values for the physical and mechanical properties are presented in Tables 1 and 2. Variance analysis of the data indicated that the internode position had no significant effect on the shearing and bending properties of both varieties. There was significant difference between the two varieties in the case of Young's modulus at 1% probability level, while there was not any difference in the case of shear strength, specific shearing energy and bending strength. The interaction effect of variety × internode on the shearing and bending properties was not significant (P>0.05). The results obtained are discussed in detail as follows.

Physical properties

The mean values for the physical properties of sugar cane stalk varieties are presented in Table 1. According to the Duncan's multiple range tests, the averages of stalk's diameter, cross-section area and second moment of area of L310 variety were higher than those of L820 variety (P<0.01), while the average of stalk's length of L820 variety was higher than that of L310 variety (P<0.05). There were not significant differences among internodes of the stalks in the case of diameter, cross-section area and second moment of area (P>0.05), while the effect of internode position on the stalk's length was significant at 1% probability level. The stalk's length of lower internodes was greater than that of higher internodes. The averages of stalk's diameter, cross-section area, second moment of area and length of L310 and L820 varieties were 19.07 and 17.21 mm, 290.39 and 234.59 mm^2, 7188.89 and 4512.93 mm^4, and 77.63 and 83.17 mm, respectively.

Shear strength

The mean values of the shear strength of the sugar cane stalk varieties at different internode positions are presented in Table 2 and Fig. 3. According to the Duncan's multiple range tests, the values of the shear strength of the internodes were similar. In addition, there was not any difference between the two varieties in the case of shear strength. The average shear strength of L310 and L820 varieties was obtained as 4.92 and 5.25 MPa, respectively. 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 in the crop on the shear strength of alfalfa stems was studied by Nazari Galedar et al. (2008). It was 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. (2009) showed that the shear strength of wheat straw increased towards the third internode position.

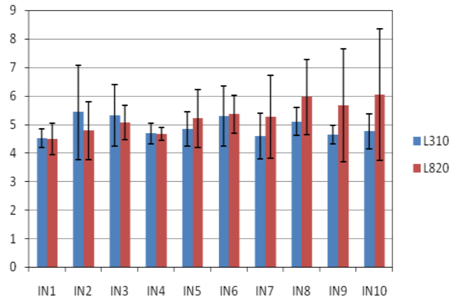

Fig.3. Shear strength of sugar cane stalks (L310 and L820 varieties) at different internode positions

Specific shearing energy

The specific shearing energy for the two varieties at different internode positions is presented in Table 2 and Fig. 4. By using Duncan's multiple range tests, the average specific shearing energy for the two varieties and the ten internodes was similar.

This means that the energy requirement for shearing of L310 and L820 varieties is same. The mean specific shearing energy of L310 and L820 varieties was obtained as 53.36 and 57.35 mJ mm^{-2}, respectively. 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.).

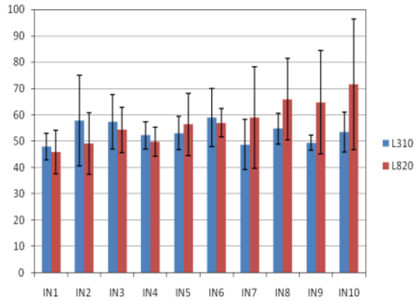

Fig.4. Specific shearing energy of sugar cane stalks (L310 and L820 varieties) at different internode positions

Bending strength

The bending strength of sugar cane stalk at different varieties and internodes are shown in Table 2 and Fig. 5. According to the Duncan's multiple range tests, there was no difference among bending strength of the internodes. In addition, the average of bending strength of L310 and L820 varieties was similar. It was 9.58 and 9.20 MPa, for L310 and L820 varieties, respectively. The values obtained in the current study for sugar cane stalk 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., 2009). Therefore, the sugar cane stalk is more flexible in comparison with sorghum stalk, alfalfa stem and wheat straw.

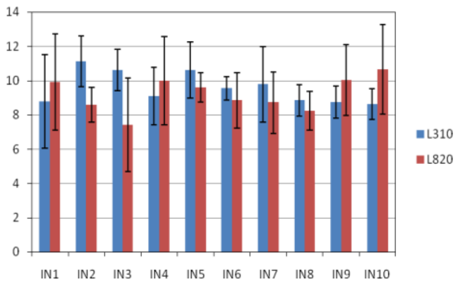

Fig.5. Bending strength of sugar cane stalks (L310 and L820 varieties) at different internode positions

Young's modulus

The mean values of the Young's modulus of the sugar cane stalk varieties at different internode positions are presented in Table 2 and Fig. 6. According to the Duncan's multiple range tests, there was no difference among Young's modulus of the internodes, however, the average of Young's modulus of L820 variety was significantly higher (P<0.01) than that of L310 variety. It was 18.81 and 24.50 MPa, for L310 and L820 varieties, respectively. The values of the Young's modulus for sugar cane stalk 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., 1989; Nazari Galedar et al., 2008).

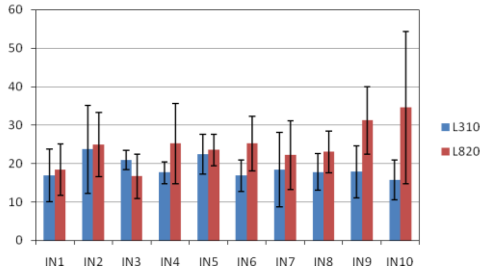

Fig.6. Young's modulus of sugar cane stalks (L310 and L820 varieties) at different internode positions

Conclusions

In this research, physical properties such as diameter, cross-section area, second moment of area and internode length, and mechanical properties including shear strength, specific shearing energy, bending strength and Young's modulus of two varieties of sugar cane stalk were investigated:

1. Based on the results obtained, the internode position had no significant effect on the shearing and bending properties of both varieties. In addition, there was significant difference between the two varieties in the case of Young's modulus at 1% probability level, while there was not any difference in the case of shear strength, specific shearing energy and bending strength. The average of Young's modulus of L820 variety was significantly higher ($P<0.01$) than that of L310 variety.
2. The mean values of shear strength, specific shearing energy, bending strength, and Young's modulus of L310 and L820 varieties were obtained as 4.92 and 5.25 MPa, 53.36 and 57.35 mJ mm^{-2}, 9.58 and 9.20 MPa, and 18.81 and 24.50 MPa, respectively.
3. This paper concludes with information on engineering properties of sugar cane stalk 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 sugar cane stalk harvesting and processing.

Acknowledgments

The authors would like to thank the agro-industry of Mirza Kouchak Khan for providing the test stems of sugar cane and University of Tehran for providing the laboratory facilities and financial support for this research.

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Table 1-Physical properties of L310 and L820 varieties

	L310									
height	IN1*	IN2	IN3	IN4	IN5	IN6	IN7	IN8	IN9	IN10
N	10	10	10	10	10	10	10	10	10	10
D	18.50	18.16	18.25	18.57	18.45	18.88	19.37	19.55	20.24	20.74
(mm)	(1.94)	(1.91)	(1.98)	(2.03)	(1.75)	(2.30)	(2.82)	(2.74)	(3.03)	(3.21)
A	271.48	261.64	264.43	273.76	269.66	283.71	300.32	305.51	328.25	345.14
(mm^2)	(57.97)	(52.58)	(56.08)	(59.76)	(50.15)	(67.91)	(90.92)	(87.29)	(100.36)	(112.58)
I_b	6105	5645.37	5789.51	6219.90	5966.95	6735.78	7769.26	7973.06	9295.94	10387.30
(mm^4)	(269.05)	(211.09)	(232.18)	(275.61)	(215.62)	(311.82)	(494.57)	(466.87)	(580.26)	(736.82)
L	63.29	70.65	71.34	78.82	80.34	73.55	77.83	85.39	86.13	88.96
(mm)	(18.24)	(12.37)	(14.82)	(23.57)	(15.01)	(12.85)	(21.79)	(23.78)	(15.06)	(14.42)
L820										
D	16.79	17.42	17.82	17.65	17.19	17.01	17.19	17.30	16.97	16.81
(mm)	(1.65)	(1.30)	(1.76)	(1.20)	(1.38)	(1.65)	(1.52)	(1.71)	(1.73)	(1.67)
A	223.34	239.67	251.59	245.68	233.42	229.17	233.73	237.11	228.30	223.89
(mm^2)	(43.24)	(35.84)	(49.69)	(33.08)	(36.57)	(45.03)	(41.40)	(45.90)	(45.58)	(42.46)
I_b	4103.19	4663.32	5213.96	4881.85	4431.81	4324.61	4470.09	4624.97	4296.63	4118.41
(mm^4)	(153.44)	(137.97)	(204.17)	(129.18)	(132.74)	(174.21)	(158.7)	(171.51)	(167.31)	(143.12)
L	70.03	74.86	74.6	84.10	89.19	92.36	94.97	87.67	84.31	79.63
(mm)	(16.49)	(13.08)	(10.05)	(23.53)	(31.28)	(18.87)	(22.79)	(18.01)	(26.55)	(24.83)

*IN1, IN2 … and IN10: first, second … and tenth internodes, respectively; N: number of observations; D: diameter of stalk; A: cross–section area; L: length; figures in parentheses are standard deviation.

Table 2- Shearing and Bending characteristics of sugar cane stalks (L310 and L820 varieties) at different internode positions

L310										
height	IN1*	IN2	IN3	IN4	IN5	IN6	IN7	IN8	IN9	IN10
N	5	5	5	5	5	5	5	5	5	5
τ_s (MPa)	4.51_{a} (0.32)	5.43_{a} (1.65)	5.32_{a} (1.07)	4.67_{a} (0.36)	4.84_{a} (0.59)	5.29_{a} (1.04)	4.59_{a} (0.80)	5.10_{a} (0.49)	4.65_{a} (0.32)	4.76_{a} (0.61)
E_{sc} ($mJ\ mm^{-2}$)	47.96_{bc} (5.10)	57.85_{abc} (17.19)	57.34_{abc} (10.33)	52.22_{bc} (5.14)	53.02_{bc} (6.29)	58.90_{abc} (11.01)	48.73_{bc} (9.54)	54.79_{abc} (5.83)	49.41_{bc} (2.87)	53.38_{bc} (7.60)
σ_b (MPa)	8.78_{abc} (2.71)	11.13_{a} (1.48)	10.62_{ab} (1.21)	9.10_{abc} (1.67)	10.60_{ab} (1.63)	9.54_{abc} (0.67)	9.79_{abc} (2.20)	8.83_{abc} (0.91)	8.75_{abc} (0.92)	8.63_{abc} (0.88)
E (GPa)	16.87_{c} (6.86)	23.72_{abc} (11.45)	20.94_{bc} (2.46)	17.65_{c} (2.83)	22.37_{bc} (5.16)	16.81_{c} (4.08)	18.44_{c} (9.67)	17.79_{c} (4.77)	17.83_{c} (6.76)	15.69_{c} (5.18)
L820										
τ_s (MPa)	4.48_{a} (0.55)	4.78_{a} (1.01)	5.07_{a} (0.60)	4.66_{a} (0.23)	5.20_{a} (1.01)	5.36_{a} (0.67)	5.27_{a} (1.46)	5.96_{a} (1.31)	5.67_{a} (1.97)	6.05_{a} (2.30)
E_{sc} ($mJ\ mm^{-2}$)	45.84_{c} (8.29)	49.08_{bc} (11.67)	54.28_{abc} (8.61)	49.77_{bc} (5.45)	56.38_{abc} (11.78)	56.98_{abc} (5.30)	58.92_{abc} (19.31)	65.88_{ab} (15.47)	64.79_{ab} (19.62)	71.60_{a} (24.87)
σ_b (MPa)	9.92_{abc} (2.79)	8.59_{abc} (1.02)	7.41_{c} (2.73)	9.98_{abc} (2.58)	9.60_{abc} (0.86)	8.84_{abc} (1.62)	8.72_{abc} (1.79)	8.23_{bc} (1.12)	10.03_{abc} (2.05)	10.66_{ab} (2.60)