Effect of Moisture Content and Loading Rate on the Shearing Characteristics of Barley Straw by Internode Position

H. Tavakoli*; S.S. Mohtasebi; A. Jafari

Department of Agricultural Machinery Engineering, Faculty of Biosystems Engineering, University of Tehran , P.O. Box 4111, Karaj 31587-77871, Iran

*Corresponding email: H8.Tavakkoli@gmail.com

ABSTRACT

This research was conducted to evaluate the effect of moisture content, internode position and loading rate on the shearing characteristics of barley straw in terms of shear strength and shearing energy. The characteristics were determined at three moisture levels: 10, 15 and 20 % w.b., three loading rates: 5, 10 and 15 mm/min and three internodes: first, second and third internode. The results showed that both the shear strength and shearing energy increased with an increase in moisture content and loading rate and towards the third internode position. The average shear strength was obtained as 5.08 MPa varying from 3.68 to 6.18 MPa, while the average shearing energy was calculated as 100.93 mJ ranging from 65.17 to 131.06 mJ. The shear strength of the barley straw increased from 4.09 to 5.03 MPa, 4.84 to 5.25 MPa and 5.15 to 5.94 MPa for the first, second and third internodes, respectively, as the moisture content increased. The shearing energy of the straw also varied from 70.44 to 99.82 mJ, 92.46 to 121.25 mJ and 102.33 to 122.09 mJ for the first, second and third internodes, respectively.

Keywords: Barley, moisture content, loading rate, shear strength, shearing energy, Instron SMT-5

1. INTRODUCTION

Barley (*Hordeum vulgare* L.) is a member of the grass family *Poaceae*. In Iran, barley is widely cultivated on approximately 1,817,572 ha with an annual production of 2,900 kt (FAO, 2006). Several tons of straw are produced from this crop annually. These straws are usually served as animal nutrition and sometimes incorporated into the plowed layer or used as mulch. For these purposes, straw must be processed (e.g. threshing, handling, etc.) after harvesting. For selecting design and operational parameters of equipment relating to harvesting, threshing, handling and other processing of barley straw, it is necessary to know physical and mechanical properties of it.

Most studies on the mechanical properties of plants have been carried out during their growth using failure criteria (force, stress and energy). Studies have focused on plant anatomy, lodging processes, harvest optimisation, animal nutrition, industrial applications and the decomposition of wheat straw in soil (McNulty and Moshenin, 1979; Annoussamy et al., 2000; Skubisz et al., 2007). 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 (Bright and Kleis, 1964; Persson, 1987). These physical properties are also different depending on the heights of the plant stalk and loading rates.

Several works have been conducted to determine the mechanical properties of plants. 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 MPa and 59–128 MPa, with maximum at moisture contents of 20 % w.b. and 35 % w.b. for the two sets of data. The shape of the curves relating shear strength to moisture content were analogous to those found by Liljdall et al. (1961) who investigated the specific energy required to cut beds of forage. Kushwaha et al. (1983) reported mean values of shear strength of wheat straw in the range of 8.6-13.0 GPa with some dependence on moisture content. Other researchers have measured the specific energy required to shear materials. Shinners et al. (1987) found that longitudinal shearing of alfalfa stems required less than 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 $mJ.mm^{-2}$. Prasad and Gupta (1975) found that the cross-sectional area and moisture content of the crop had a significant effect on the cutting energy and the maximum cutting force. Similar results were also reported by Choi and Erbach (1986). Sakharov et al. (1984) reported that the required force to cut stretched (bent) stalks was 50 % less than that for straight stalks.

Similar works have been conducted in recent years such as: Chen et al. (2004) on hemp stem, İnce et al. (2005) on sunflower stalk and Nazari Galedar et al. (2008) on alfalfa stems. It seems that there is not any published work relating to the mechanical properties of barley straw. Therefore, the objective of this study was to investigate the effect of moisture content, internode position and loading rate on the shearing characteristics of barley straw including shear strength and shearing energy.

2. MATERIALS AND METHODS

The barley stem (cv. 'Nosrat') used for the present study is one of the prevalent cultivars of barley in Iran and was obtained from agronomy farm of the Seed and Seedling Research Institute, Karaj, Iran. The stems were collected at harvest and their internodes were separated out according to their position down from the ear (fig. 1) (Announssamy et al., 2000). Leaf blades and sheaths were removed prior to any treatment or measurement. To determine the average moisture content of the barley stems, the specimens were weighed and oven-dried at 103 °C for 24 h (ASAE, 2006) and then reweighed. To attain desired moisture levels, samples 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 rewetted samples were then transferred to separate plastic bags and the bags sealed tightly. The samples were kept at 5°C in a refrigerator for a week to enable the moisture to be distributed uniformly throughout the samples. After that, the specimens were taken out of the refrigerator and allowed to warm up to room temperature for about 2 h. The specimens were then reweighed to specify amounts of water absorbed by them. By calculating the amount of water absorbed and using the equation (1), moisture content of the straw specimens was attained. The experiments were conducted at moisture levels of 10 %, 15 % and 20 % w.b. Three internodes of barley 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 investigated because these internodes are usually left on the field. The experiments were performed at loading rates of 5, 10 and 15 mm/min.

2.1. Experimental Procedure

The shearing characteristics of barley 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. (2008) (fig. 2). The measurements were made using a proprietary tension/compression testing machine (Instron Universal Testing Machine SMT-5, SANTAM Co., Iran).

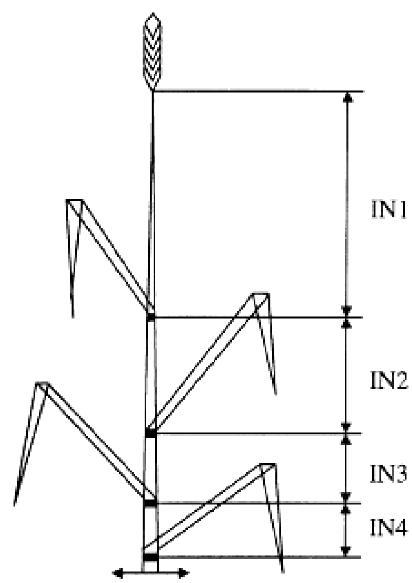

Figure 1. Diagram of straw identifying internodes.

The shear strength was measured in double shear using a shear box (fig. 2) 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 diameter ranging from 1.5 to 5 mm were drilled through the plates to accommodate internodes of different diameter. Shear force was applied to the straw specimens by mounting the shear box in the tension/compression testing machine. 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:

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

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 was calculated by integrating the curves of shear force and displacement (Chattopadhyay and Pandey, 1999; Chen et al., 2004; Nazari Galedar et al., 2008) using a standard computer program (version 5, SMT Machine Linker, SANTAM Co., Iran). An example of the shear force versus displacement curves is shown in figure 3. 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.

2.2. Experimental Design and Statistical Analysis

This study was planned as a completely randomized block design. The experiments were conducted with five replications in each treatment. Experimental data were analysed using analysis of variances (ANOVA) and the means were separated at 5 % and 1 % probability levels applying Duncan's multiple range test in SPSS (version 15, SPSS Inc., USA) software.

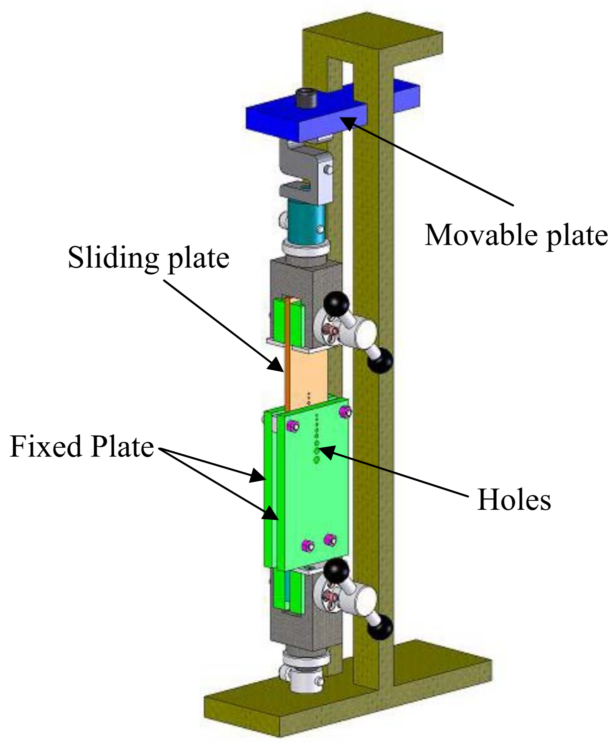

Figure 2. Apparatus for the measurement of shearing characteristics of straw internodes.

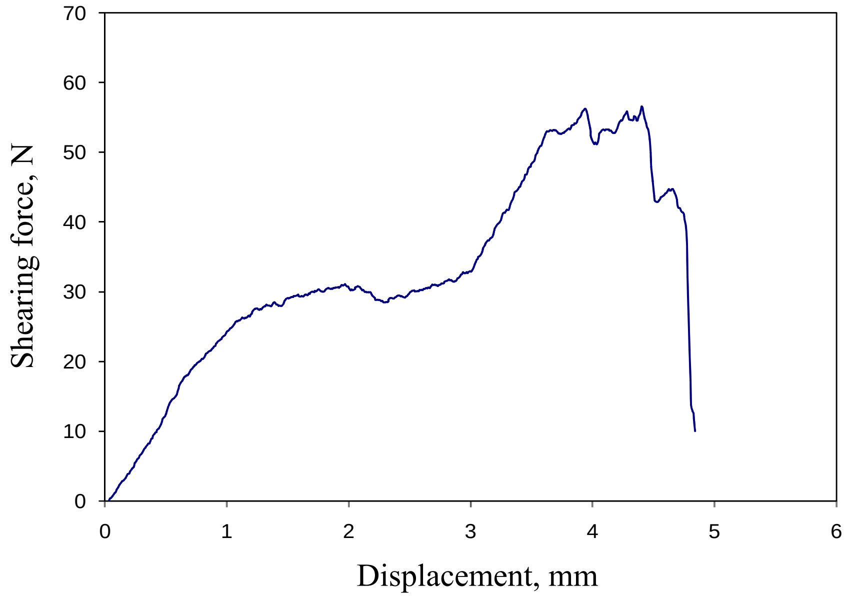

Figure 3. Shearing force versus displacement curve for barley straw

3. RESULTS AND DISCUSSION

The variance analysis of the data indicated that the moisture content, internode position and loading rate created a significant effect on the shear strength and shearing energy ($P<0.01$). The average shear strength was obtained as 5.08 MPa varying from 3.68 to 6.18 MPa, while the average shearing energy was calculated as 100.93 mJ ranging from 65.17 to 131.06 mJ. Based on the statistical analysis, interaction effects of moisture content × loading rate, internode × loading rate and moisture content × internode × loading rate on the shear strength and shearing energy were not significant ($P>0.05$). The interaction effect of moisture content × internode on the shearing energy was significant at 5 % probability level but the effect on the shear strength was not significant ($P>0.05$).

In the following paragraphs, the effects of each factor on the shear strength and shearing energy are comprehensively discussed.

3.1. Moisture Content

The moisture content had a significant effect ($P<0.01$) on the shear strength and shearing energy as shown in table 1. The shear strength and shearing energy increased with an increase in the moisture content which may be due to the drier straw being more brittle. Similar results have been reported by most previous researchers (McRandal and McNulty, 1980; Annoussamy et al., 2000; Nazari Galedar et al., 2008). The shear strength of the barley straw increased from 4.09 to 5.03 MPa, 4.84 to 5.25 MPa and 5.15 to 5.94 MPa for the first, second and third internodes, respectively, as the moisture content increased (fig. 4). The shearing energy of the straw varied from 70.44 to 99.82 mJ, 92.46 to 121.25 mJ and 102.33 to 122.09 mJ for the first, second and third internodes, respectively (fig. 5). The interaction effect of moisture content × internode on the shear strength and shearing energy is presented in table 2. Considering the results obtained, for severing and threshing the barley straw, lower moisture content can be recommended to minimize the shearing force and shearing energy requirements.

Table 1. Comparison of shear strength and shearing energy of barley straw in different moisture contents, loading rates and internode positions

Moisture content (% w.b.)	Shear strength (MPa)*	Shearing energy (mJ)*
10	4.692	88.410
15	5.128[a]	99.990
20	5.406[a]	114.388
Loading rate (mm/min)		
5	4.728	92.671
10	5.104[b]	101.464[c]
15	5.393[b]	108.653[c]
Internode position		
IN1	4.638	87.159
IN2	5.074	105.882[d]
IN3	5.513	109.746[d]

* Mean values with common index are not significantly different (P>0.05) according to Duncan's multiple ranges test.

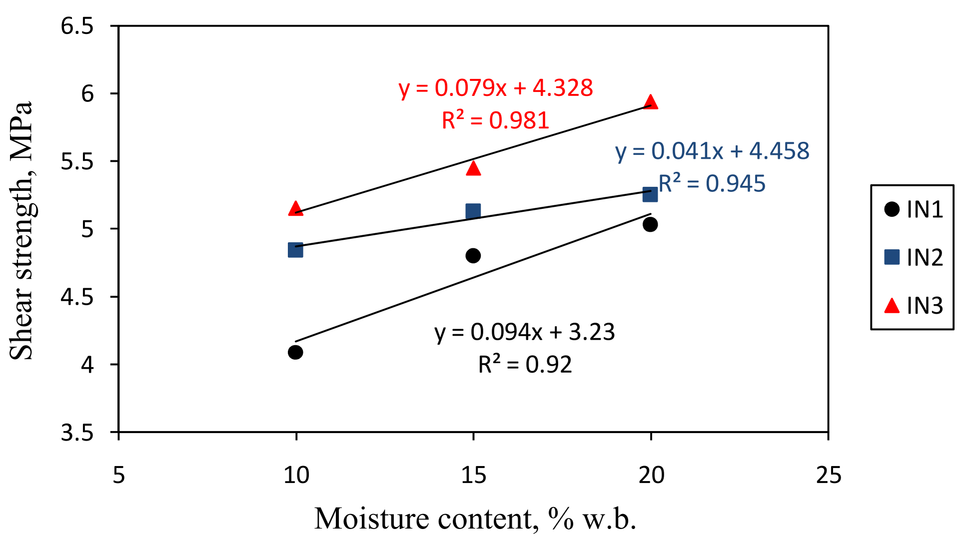

Figure 4. Effect of moisture content and internode position on the shear strength.

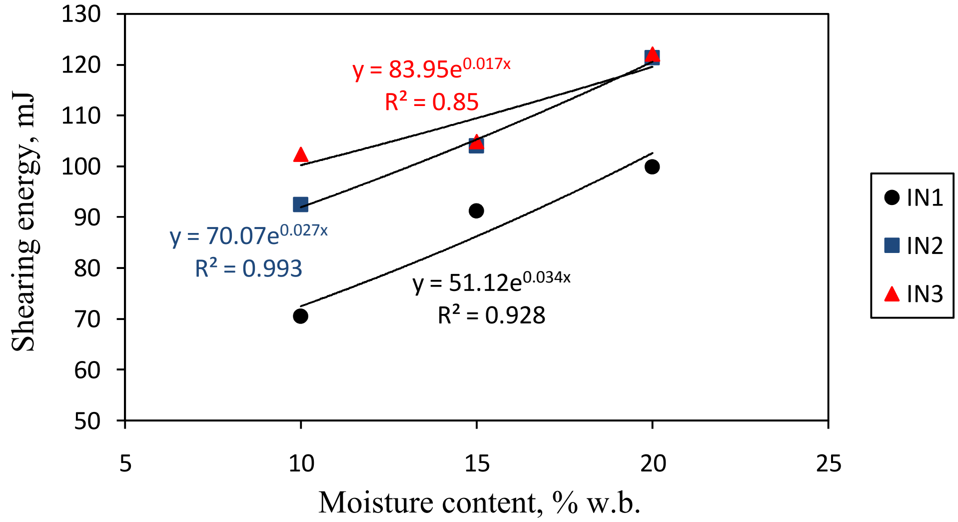

Figure 5. Effect of moisture content and internode position on the shearing energy.

3.2. Loading Rate

The mean values of the shear strength and shearing energy at different loading rates are presented in table 1. It is observed that the shear strength and shearing energy of the straw increased significantly (P<0.01) with an increase in the loading rate. This effect of loading rate was also reported by El Hag et al. (1971) for cotton stalk. Mohsenin et al. (1963) also found that the rate of deformation affected the maximum force that could be exerted by a steel plunger on apples. As the rate of deformation increased, the maximum force of rupture increased. As shown in figure 6, the shear strength of the barley straw increased from 4.24 to 4.98 MPa, 4.72 to 5.40 MPa and 5.22 to 5.80 MPa for the first, second and third internodes, respectively, as the loading rate increased from 5 to 15 mm/min. The shearing energy of the straw varied from 81.05 to 119.28 mJ in the first internode under lowest loading rate and third internode under highest loading rate, respectively (fig. 7). The interaction effect of loading rate × internode on the shear strength and shearing energy is presented in table 3.

Table 2. Comparison of shear strength and shearing energy of barley straw considering interaction effect between moisture content and internode position

Moisture content (% w.b.)	Internode position*					
	Shear strength (MPa)			Shearing energy (mJ)		
	IN1	IN2	IN3	IN1	IN2	IN3
10	4.090 [a]	4.837 [b]	5.149 [b]	70.443 [a]	92.459 [bc]	102.328 [d]
15	4.797 [b]	5.134 [b]	5.452 [bc]	91.212 [b]	103.934 [d]	104.823 [d]
20	5.028 [b]	5.251 [b]	5.938 [c]	99.823 [cd]	121.253 [e]	122.088 [e]

* Mean values with common index are not significantly different (P>0.05) according to Duncan's multiple ranges test.

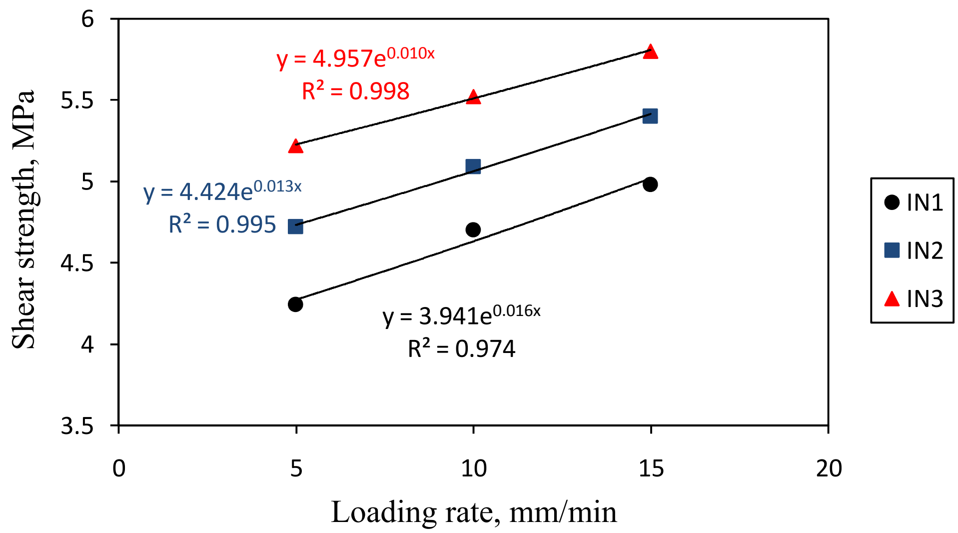

Figure 6. Interaction effect of loading rate and internode position on the shear strength.

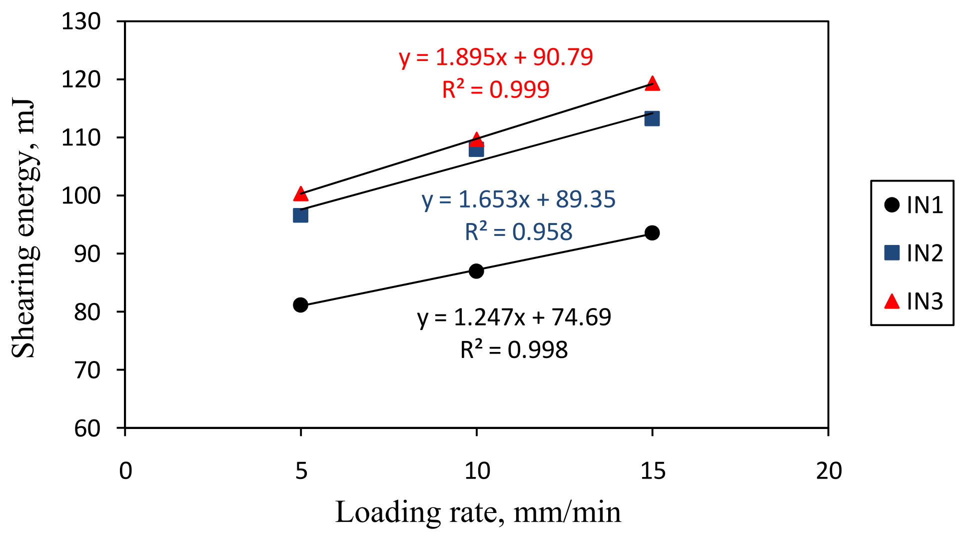

Figure 7. Interaction effect of loading rate and internode position on the shearing energy.

3.3. Internode Position

The shear strength and shearing energy were significantly affected by internode at 1 % probability level. The values increased towards the third internode position as shown in figures 4, 5, 6 and 7. The mean values of the characteristics at different internodes are presented in table 1. It is observed that the shear strength and shearing energy of the straw increased from 4.64 to 5.51

MPa and 87.16 to 109.75 mJ, respectively, towards the third internode position. It was probably greater in the lower levels because of the accumulation of more mature fibres in the stem. This effect of the level of stem on the shear strength and shearing energy was also reported by İnce et al. (2005) for sunflower stalk and Nazari Galedar et al. (2008) for alfalfa stems. The interaction effects of internode × moisture content and internode × loading rate on the shear strength and shearing energy are presented in table 2 and 3, respectively.

Table 3. Comparison of shear strength and shearing energy of barley straw considering interaction effect between loading rate and internode position

Loading rate (mm/min)	Internode position*					
	Shear strength (MPa)			Shearing energy (mJ)		
	IN1	IN2	IN3	IN1	IN2	IN3
5	4.239 [a]	4.724 [ab]	5.222 [bcd]	81.049 [a]	96.633 [c]	100.331 [cd]
10	4.697 [ab]	5.095 [bcd]	5.518 [cd]	86.907 [ab]	107.858 [de]	109.628 [e]
15	4.978 [bc]	5.402 [bcd]	5.800 [d]	93.522 [bc]	133.157 [ef]	119.281 [f]

* Mean values with common index are not significantly different (*P*>0.05) according to Duncan's multiple ranges test.

4. CONCLUSIONS

The following conclusions were drawn from the investigation of the effects of moisture content, internode position and loading rate on the shear strength and shearing energy of barley straw.

1. Both shear strength and shearing energy increased with an increase in moisture content and loading rate and towards the third internode position.
2. The shear strength varied from 3.68 to 6.18 MPa, and the shearing energy ranged from 65.17 to 131.06 mJ.
3. Considering the results obtained, for severing and threshing the barley straw, lower moisture contents can be recommended to minimize the shearing force and shearing energy requirements.

This paper concludes with information on engineering properties of barley 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 barley straw harvesting and processing.

5. ACKNOWLEDGEMENTS

The authors would like to thank the Seed and Seedling Institute Research for providing the test stems of barley straw and the University of Tehran for providing the laboratory facilities and financial support for this project. The authors are also grateful to Mehrdad Nazari and Mahdi Tavakoli for their helps.

6. REFERENCES

Annoussamy, M., G. Richard, S. Recous and J. Guerif. 2000. Change in mechanical properties of wheat straw due to decomposition and moisture. *Applied Engineering in Agriculture*, 16(6), 657–664.

ASAE Standards, 52nd Ed (2006). S358.2: 1:1 measurement - forages. St. Joseph, MI: ASABE.

Bright, R.E. and R.W. Kleis. 1964. Mass shear strength of haylage. *Transactions of the ASAE*, 7(2), 100–101.

Chattopadhyay, P.S. and K.P. Pandey. 1999. Mechanical properties of sorghum stalk in relation to quasi-static deformation. *Journal of Agricultural Engineering Research*, 73, 199–206.

Chen, Y., J.L. Gratton and J. Liu. 2004. Power requirements of hemp cutting and conditioning. *Biosystems Engineering*, 87(4), 417–424.

Choi, C.H. and D.C. Erbach. 1986. Corn stalk residue shearing by rolling coulters. *Transactions of the ASAE*, 29(6), 1530–1535.

Dernedde, W. 1970. Die technologischen eigenschaften von gras und deren einfluss den schneidvorgang (Technological properties of grass and their influence on the cutting process). "*Zerkleinern Von Halmfutter" LandbForseh- Völkenrode. Sondern*, 8, 53–57.

El Hag, H.E., O.R. Kunze and L.H. Wilkes. 1971. Influence of moisture, dry-matter density and rate of loading on ultimate strength of cotton stalks. *Transaction of the ASAE*, 4(2), 713–716.

FAO, (2006). FAOSTAT database. http://faostat.fao.org/faostat/ (accessed: 11 Dec., 2008).

İnce, A., S. Uğurluay, E. Güzel and M.T. Özcan. 2005. Bending and shearing characteristics of sunflower stalk residue. *Biosystems Engineering*, 92(2), 175–181.

Kushwaha, R.L., A.S. Vashnav and G.C. Zoerb. 1983. Shear strength of wheat straw. *Canadian Agricultural Engineering*, 25(2), 163–166.

Liljedhal, J.B., G.L. Jackson, R.P. Graff and M.E. Schroeder. 1961. Measurement of shearing energy. *Agricultural Engineering*, 42, 298–301.

McNulty, P.B. and N.N. Moshenin. 1979. Compaction of bulk corn carnal to failure. *Transactions of the ASAE*, 22(2), 264–269.

McRandal, D.M. and P.B. McNulty. 1980. Mechanical and physical properties of grasses. *Transactions of the ASAE*, 23(4), 816–821.

Mohsenin, N.N. 1986. *Physical properties of plants and animal materials*. Gordon and Breach Science Publishers, New York.

Nazari Galedar, M., A. Tabatabaeefar, A. Jafari, A. Sharifi and S. Rafee. 2008. Bending and shearing characteristics of alfalfa stems. *Agricultural Engineering International: the CIGR Ejournal,* Manuscript FP 08 001. Vol. X.

O'Dogherty, M.J., J.A. Hubert, J. Dyson and C.J. Marshall. 1995. A study of the physical and mechanical properties of wheat straw. *Journal of Agricultural Engineering Research*, 62, 133–142.

Persson, S. 1987. Mechanics of Cutting Plant Material. *ASAE Publications, Michigan.*

Prasad, J. and C.B. Gupta. 1975. Mechanical properties of maize stalks as related to harvesting. *Journal of Agricultural Engineering Research*, 20(1), 79–87.

Sakharov, V.V., G.G. Rakmanberdiev and G.G. Guagev. 1984. An investigation into the severing of pre-tensed mulberry stems by a screw-type cutter. *Mekhanizatsiya i Elekfikikatsiya Sel'Skaogo Khozyaistva*, 3, 61–62.

Shaw, M. and L. Tabil. 2006. Mechanical properties of selected biomass grinds. ASABE Annual International Meeting, Oregon Convention Center, Portland, Oregon 9 - 12 July 2006.

Shinners, et al. 1987. Evaluating longitudinal shear as a forage maceration technique. *Transactions of the ASAE*, 30(1), 18–22.

Skubisz, G., T.I. Kravtsova and L.P. Velikanov. 2007. Analysis of the strength properties of pea stems. *International Agrophysics*, 21, 189–197.