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DETERMINING THE PHYSICO-MECHANICAL CHARACTERISTICS OF MAIZE STALKS FORDESIGNING HARVESTER

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ABSTRACT

Physical characteristics of crops and plants are significant issues in designing machinery to harvest them.Therefore in the present study, general physical properties, bending stress, modulus of elasticity, shear stress and specific shearing energy were determined over stalks of 10 different maize (*Zeamays* L.) cultivars. Test specimens were taken from three different locations of stalks as of upper section, middle section and bottom section. Average moisture contents of upper, middle and bottom sections were respectively observed as 78.18, 73.87 and 69.91%. The average bending force varied between 40 -459.3N and the average modulus of elasticity varied between 10.04- 673.84 MPa. The modulus of elasticity decreased with increasing stalk diameters. Variance analysis revealed that Bora, SX-689, MocejonI and DK-585 were similar cultivars and their modulus of elasticity were greater than the other cultivars (P<0.01). The results also showed decreasing shearing stress and specific shearing energy values toward the upper sections of the stalks. The maximum shearing stress and the specific shearing energy were 5.27MPa and 213.03 mJmm^{-2}, respectively. According to variance analysis, the cultivarsSX-689 and Mocejon-I were also found to be as similar varieties and their specific shearing energies were greater than the other cultivars (P < 0.01). Both the shearing stress and specific shearing energy were found to be higher along the bottom section of the stalks due to the structural heterogeneity.

Key word: Maize, bending stress, modulus of elasticity, shearing stress, specific shearing energy.

INTRODUCTION

Maize silage is cultivated over 337.159ha land area with 14.9million ton annual production and 44500kgha^{-1} yield in Turkey (TUIK, 2012). It is the third cereal crop of the country after wheat and barley.Maize has a remarkable place in human and animal feeding and a significant industrial cash crop. Of the annual production, 35% is used for human nutrition, 30% is used for animal feeding and 20% is used in again livestock feed industry. It is also a silage crop and cultivation lands are increasing in each day (Keskin *et al.*,2005). Maize is harvested with silage machines and combine harvesters.The cultivar plays a significant role in the specific energy consumptionof the harvester. Through selection of proper cultivar, considerable savings can be achieved in specific energy consumption of the harvesters and silage machines. Therefore, physico-mechanical characteristics of maize stalks should be known or determined for proper operation of such devices. Among those characteristics, compression, tension, bending, density and friction are the most significant ones influencing the harvest of corn stalks. Such characteristics totally depend on species, variety, stalk diameter, maturity, moisture content and cellular structure (Bright andKleis, 1964; Persson, 1987). Thosecharacteristics also vary from one section to another of the stalks. Empirical methods are not sufficient alone in design of plant handling and processing equipment without a previous knowledge of physic-mechanical characteristics of the relevant plant or crop.Thus, physical properties of agricultural materials are very important for designing machinery for them.

Various studies have been conducted to determine the mechanical properties of plants and crops. Curtis and Hendrick (1969) determined that the section modulus in bending varied with the third power of the diameter for cotton stalks of diameters ranging from 7 to 16 mm. The modulus of elasticity varied from 600 to 3500 MPa. Prince *et al.*(1969) studied the modulus of rigidity of green lucerne and oven-dried specimens and observed the mean values of 0.225 and 1.45 GPa, respectively. Sakharow *et al.* (1984) reported that the required force to cut the stretched stalks was 50% less than that of unbelted stalks. Chattopadhyay and Pandey (1999) determined the bending stress for sorghum as 40-53 MPa and 45-65 MPa at the seed stage and forage stage, respectively.

Prasad and Gupta (1975) emphasized that the cross-sectional area and moisture content of the crop had significant effects on cutting energy and maximum cutting force. Similar results were also reported by Choi and Erbach (1986). They also studied the mechanical properties of alfalfa stems and observed maximum shearing stresses ranging between 0.4 and 18.0 MPa depending on moisture content. McRandal and McNulty(1980) conducted shearing experiment on field grasses and observed a shearing stress of 16 MPa and shearing energy of 12.0 mJmm^{-2}. Chen *et al.*(2004)

reported the maximum force and the total cutting energy for hemp as 243 N and 2.1 J, respectively. Ince*et al.*(2005) determined bending and shearing characteristics of sunflower stalk residues and reported specific shearing energy for sunflower stalk as between 1.86-8.5, 1.7-10.7 and 2.4-11.0 $mJmm^{-2}$ at the upper, middle and lower sections, respectively.

Considering the above points, there is a need for research about the variations in physico-mechanical properties of maize stalks to improve the chopping conditions. Therefore, the present study was focused on bending stress, modulus of elasticity in bending, shear stress and specific shearing energy of three different sections of stalks of 10 different maize cultivars.

MATERIALS AND METHODS

Research plan: Three groups of experiments were conducted in this study. The first group included basic physicalcharacteristics such as length, diameter, cross-sectional area and moisture content. The second group was conducted for three-point loading to test the strength in bending. The third group was composed of the tests madeto determinethe shearing stress and shearing energy. The maize cuttings operationsof the experiments were conducted at BahriDağdaş International Agricultural Research Institute, Konya. All the tests were carried out under laboratory conditions. The classified stalk samples were preserved in plastic bags until test times. Upper, middle and bottom sections of stalk samples were designated and sheared in certain lengths to use in experiments. Before the tests, malformed cuttings were discarded. The tests were performed over 10 different cultivars (Bora, SX-689, Montai, MocejonI, Progen-1490, Progen-1550, DKC-6022, P-31G98, DK-585 and P-3394). In brief, three groups of experiments (basic characteristics, bending strength and shearing strength) were conducted overthreesections (upper, middle and bottom) of stalks with 10 samples for each group.

Experimental Procedure

Basic Characteristics: For each cutting, length of the maize stalks were measured, then the cobs and the leaves of plants were removed. Before bending and shearing tests, diameter (average diameter at the midpoint) recorded and cross-sectional areas of samples were measured. A digital camera and Sigma Scan Pro Software were used to measure cross-sectional areas. Specimens from upper, middle and bottom sections were cut approximately at 122.5 mm lengths (Simonton, 1992).To determine of the average moisture contents, specimens were weighed and dried at 102 °C for 24 h in an oven and reweighed. The diameter of the maize stalks decreased towards the top of the plant. That means the maize stalk shows different physico-mechanical properties at different heights due to cross-sectional area. The average diameter of the stalks in upper, middle and bottom sections respectively varied between 8.75-11.01,15.85-19.76 and 23.08 -26.66 mm.The basic characteristics of each cultivar are provided in Table 1.

Bending Strength: Beam tests provide information on strength in bending and stiffness of the material. A three-point loading apparatus was used to determine bending strength of the specimens. The span length was 68.25 mm and the force applied from upper surface of the stalk.Support and indenting rods were 11.2 mm in diameter. Specimens were placed in the three point loading apparatus and the force was applied to the centre of the stalk. Force-versus-deformation data were recorded by the computer until fracture.

Force-deformation curves were obtained from the test data by software. The force and deformation at the bioyield peak and at the inflection point as defined by ASAE Standard S368.1 (1985) were obtained from all curves. Tangent modulus was calculated by using the slope of pseudo-elastic portion of the force-deformation curve. The tangent modulus(T) was computed for the strength in bending with the following equation (Mohsenin, 1980):

$$T = F/D \qquad (1)$$

Where: T is tangent modulus in $daNmm^{-1}$, F is force in daN and D is deformation in mm.

The values of f andD were taken from the center of the pseudo-elastic portion of the force deformation curve of the bending tests. Then, the modulus of elasticity (E_a) was computed by using following equation (Mohsenin, 1980):

$$E_a = \frac{f\, l^3\, 10^6}{48\, D\, \pi\, d^4 / 64} \qquad (2)$$

Where: E_a is the modulus of elasticity in Pa, f is the concentrated load at mid span in N, *l*is the effective length in mm, D is the deformation in mm and d is the diameter of the stalk in mm.

Shearing Strength: The outermost layer of the maize stalk is known as the cortex and is made up of parenchyma cells containing chloroplast. This fibrous tissue plus the tubular configuration provides the stalk strength. The outer single layer of cells of the cortex is the epidermis which may be quite thick and is covered in most cases with a waxy substance called cutin. To determine the shearing force of maize stalks, an experimental shearing apparatus was used. This test rig has three main components, which are a fixed and a moving platen, a driving unit (AC electric motor, electronic reduction unit) and a data acquisition (load-cell, personal computer card and software system). The shearing tests were conducted at 0.8 mms^{-1} knife velocity and repeated three times over the upper, middle and bottom sections of stalks of different cultivars. During the shearing tests, the shearing forces on the load-cell with respect to knife penetration were recorded by data logger. The shearing stress τ in MPa was then calculated by the following equation(Mohsenin,1980):

$$\tau = \frac{F_{s\max}}{2A} \quad (3)$$

Where: $F_{s\max}$ is the shearing force in N; and A is the cross-sectional area of the stalk at shearing plane in mm^2. Double shearing method was used in the tests. From the shearing speed and time, the knife displacement was computed and the force-versus-displacement curves were plotted for each stalk diameter. The shearing energy was calculated by using the area under these curves (Chattopadhyay and Pandey, 1999; Chen *et al*, 2004). The areas under the curves were determined by using Sigma Scan Pro Software.The specific shearing energy E_{SC} in $mJmm^{-2}$ was determined by using the following equation(Mohsenin,1980):

$$E_{SC} = \frac{E_S}{A} \quad (4)$$

Where, E_S is the total shearing energy in mJ and A is the cross-sectional area of the stalk in mm^2.

RESULTS AND DISCUSSION

Bending stress and modulus of elasticity: The bending stress was evaluated as a function of stalk diameter. The bending stress at bioyield points varied between 4.0 - 41.88daN.Decreasing bending stresses were observed with increasing stalk diameters. The average modulus of elasticity varied between 11.87-496.66 MPa. An exponential relationship was observed between modulus of elasticity and stalk diameter.Mohsenin (1980) also reported the similar results with the present findings. Bending test results are provided in Table2. Graphically the force- deformation curves of the groups were similar to each other with slight differences in magnitudes of force and deformation.

The average values for modulus of elasticity were found to be 237.07, 44.14 and 21.6 MPa for upper, middle and bottom sections of the stalks, respectively. According to the variance analysis of modulus of elasticity values, differences between cultivars and stalk sections were found to be significant (P<0.01). According to the LSD (5%) test, Bora, SX-689 and Mocejon-I werefound to be similar cultivars and their modulus of elasticity values were greater than the other cultivars.So, these cultivars have greater loading resistance and resistance to the natural conditions like wind.

Shearing stress and specific shearing energy: The maize stalk is full of juice and has a full tubular section with cellulose. Shearing test results are presented in Figure 1. Similar trends were observed for different sections of the stalks. The maize stalk has a hard structure because of the length of the plant. Therefore, the shearing stress of bottom section was higher than upper section of the stalk. The shearing stress varied between 2.75 – 4.91 MPa at moisture contentof 78.14% in bottom section, between 2.61 – 4.56 MPa at moisture content of 73.87%in middle section and between 1.64 – 2.81 MPa at moisture content of 69.91% in upper section.

Table 1. Summary of results of the basic properties testing for the maize.

Varieties	Average Length, mm	Region	Average Diameter, mm	Moisture Content, %wb
Bora	2280	Growth	10.38	66.03
		middle	19.76	72.45
		root	23.99	74.43
SX-689	2450	growth	9.9	72.17
		middle	16.82	76.21
		root	24.28	78.27
Montai	2350	growth	11.01	72.49
		middle	18.61	76.13
		root	26.66	79.15
Mocejon-I	2350	growth	9.34	66.04
		middle	19.63	73.06
		root	24.61	79.63
Progen-1490	2300	growth	9.76	64.01
		middle	18.99	70.62
		root	23.59	74.43
Progen-1550	2375	growth	10.29	68.14
		middle	18.27	72.59
		root	23.58	78.05
DKC-6022	2250	growth	10.89	73.13
		middle	19.01	73.60
		root	24.55	76.03
P-31G98	2150	growth	10.55	72.94
		middle	19.39	76.65
		root	23.60	81.22
DK-585	2225	growth	8.75	69.13
		middle	15.85	72.53
		root	23.08	76.92
P- 3394	2175	growth	10.06	65.75
		middle	18.21	64.03
		root	25.02	75.79
Average Values	2283	growth	10.10	69.91
		middle	18.61	73.87
		root	24.52	78.18
Standard Deviation	12.03	growth	1.1	3.86
		middle	1.83	4.16
		root	1.59	2.76

Table 2. Compiled data from the strength in bending tests according to the different varieties

Property	Bora	SX-689	Montai	Mocejon-I	Progen-1490	Progen-1550	DKC-6022	P-31G98	DK-585	P-3394	Average Values	Standard Deviation
Group = Growth												
Bioyield force (daN)	5.90	5.40	5.90	5.43	4.48	6.14	5.89	9.00	4.71	4.00	5.68	1.36
Bioyield deformation (mm)	2.8	4.86	5.04	3.24	5	4.56	5.92	8.74	6.86	3.61	5.06	1.77
Force (daN)	4.47	2.81	3.87	3.40	1.85	2.81	3.52	5.24	3.06	1.40	3.24	1.14
Deformation (mm)	1.34	1.88	2.5	2.28	1.92	2.16	2.6	4.04	1.54	1.42	2.16	0.79
Tangent modulus (Nmm^{-1})	3.35	1.6	1.54	1.44	0.94	1.3	1.32	1.3	1.98	1.06	1.58	0.68
Modulus of elasticity (MPa)	393.04	271.97	144.44	279.87	134.51	212.46	137.74	141.03	496.66	158.94	237.06	124.57
Group = Middle												
Bioyield force (daN)	15.91	13.77	13.77	19.72	13.29	16.86	19.96	21.39	13.29	14.01	16.19	3.11
Bioyield deformation (mm)	7.78	5.1	5.32	4.18	3.86	7.22	7.5	9.28	6.14	7.64	6.40	1.76
Force (daN)	12.33	10.67	9.48	15.0	8.29	11.38	12.57	15.2	8.52	8.29	11.17	2.6
Deformation (mm)	4.18	3.8	3.48	3.2	2.38	3.08	3.36	3.34	2.96	3.18	3.29	0.48
Tangent modulus ($daNmm^{-1}$)	3.55	2.80	2.69	4.55	3.48	3.83	3.89	4.51	3.05	2.78	3.51	0.68
Modulus of elasticity (MPa)	34.51	46.96	30.19	40.83	35.86	58.86	40.91	43.01	32.58	32.7	39.64	8.6
Group = Root												
Bioyield force (daN)	25.41	41.88	27.83	37.59	19.96	33.55	32.35	40.45	27.82	32.58	31.94	6.88
Bioyield deformation (mm)	10.28	7.38	9.54	9.4	9.04	7.86	6.9	7.46	7.56	9.34	8.47	1.17
Force (daN)	19.31	34.96	20.68	23.25	13.77	24.49	26.82	32.58	18.29	23.57	23.77	6.43
Deformation (mm)	4.1	5.26	4.72	5	3.6	4.56	4.56	4.82	3.48	4.04	4.41	0.59
Tangent modulus ($daNmm^{-1}$)	4.74	6.52	4.38	4.81	3.91	5.39	5.84	6.79	5.26	5.84	5.34	0.91
Modulus of elasticity (MPa)	19.99	25.32	11.87	18.53	17.1	26.51	22.21	29.88	24.28	20.17	21.58	5.2
Means of modulus of elasticity (MPa) between groups	149.18^{ab*}	114.75^{ab}	62.16^{b}	113.07^{ab}	62.49^{b}	99.27^{B}	66.95^{b}	71.30^{ab}	184.5^{a}	70.60^{b}		42.41

LSD (5%) = 96.63

* Means followed by the same letter in each column and each treatment aren't significantly different ($P<0.01$) according to LSD test.

Table 3. Compiled data from the strength in shearing tests according to the different varieties

Property	Bora	SX-689	Montai	Moceron-I	Progen 1480	Progen 1550	DKC 6022	P31D98	DK585	P3384	Average Values	Standard Deviation
Group = Growth												
Shearing Force (N)	609.4	776.2	838.1	907.25	707.1	802.4	928.7	721.35	547.5	690.4	752.84	122.37
Displacement (mm)	13.34	13.16	12.4	12.5	15.46	14.54	13.98	12.52	11.66	13.84	13.34	1.14
Shearing stress (MPa)	1.64	2.81	2.66	2.69	1.94	1.92	2.49	2.12	2.1	2.19	2.26	0.39
Specific Shearing energy ($mJmm^{-2}$)	37.65	46.57	46.72	43.79	39.94	38.41	41.77	35.75	38.84	41.98	41.14	3.71
Group = Middle												
Shearing Force (N)	2336.7	2794.15	2501.05	2865.55	2331.9	2877.5	2813.2	2429.6	2069	2484.4	2550.31	275.14
Displacement (mm)	25.24	19.28	18.22	18.62	21.16	18.5	19.12	13.72	19.22	19.08	19.22	2.83
Shearing stress (MPa)	2.96	4.56	2.98	3.55	2.61	3.92	3.31	3.17	2.97	3.08	3.31	0.57
Specific Shearing energy ($mJmm^{-2}$)	62.12	98.78	63.97	74.25	52.22	75.23	74.41	86.55	64.75	62.2	71.45	13.53
Group = Root												
Shearing Force (N)	3253.9	5421.5	4058.2	4759.3	3728	3542.2	4981.2	3963.9	3932.9	4033	4167.41	677.43
Displacement (mm)	18.48	21.38	19.46	18.22	19.58	15.46	18.52	15.22	15.56	14.82	17.67	2.25
Shearing stress (MPa)	2.75	4.91	3.42	4.46	3.31	3.79	3.82	3.43	3.8	3.77	3.75	0.6
Specific Shearing energy ($mJmm^{-2}$)	75.88	179.91	110.73	163.46	92.68	112.41	119.83	94.95	100.08	124.03	117.40	32.12
Means of Specific Shearing energy ($mJmm^{-2}$) between groups	58.55^{d*}	108.42^{a}	73.81^{cd}	93.83^{ab}	61.62^{cd}	75.35^{bcd}	78.67^{bc}	72.42^{cd}	67.89^{cd}	76.07^{bcd}		14.78

LSD (5%) = 19.19

* Means followed by the same letter in each column and each treatment aren’t significantly different ($P<0.01$) according to LSD test.

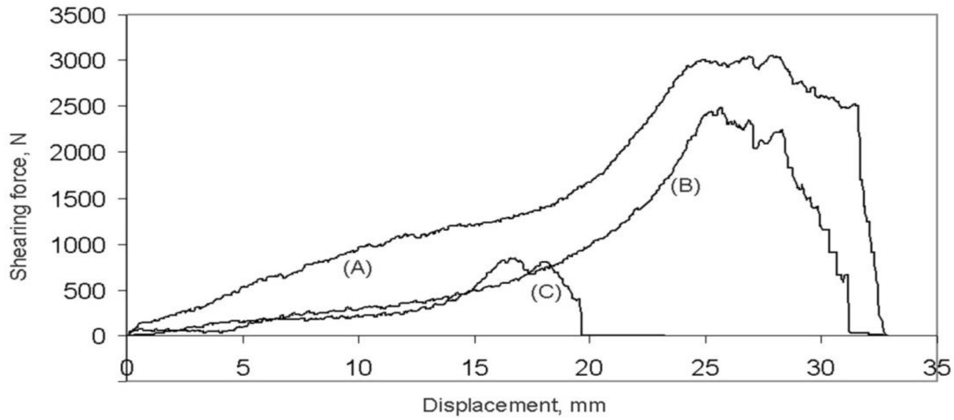

Fig. 1. Typical force - displacement curve for maize stalk; the graphics; A shows root region, B shows middle region and C shows growth region of cutting.

The specific shearing energy decreased towards the upper sections. The values of bottom, middle and upper sections respectively varied between 35.75 - 46.72, 52.22 - 98.78 and 75.88 - 179.91 mJ mm^{-2}. Shear test results for different cultivars are provided in Table 3. The value was greater in lower sections because of the diameter of the stalks. According to the variance analysis of specific shearing energy, differences between varieties and sections were found to be significant ($P<0.01$). According to the LSD (5%) test, SX-689 and Mocejon I were similar cultivars and their specific shearing energies were greater than the other cultivars.

Conclusions: A material-testing procedure has been applied to maize stalks in order to determine their bending strength, modulus of elasticity, shearing strength and specific shearing energy. Such information is needed to provide essential engineering data in the design of machines, processes and controls; in determining the efficiency of an operation. Comparison of different maize cultivars with regard to specific shearing energy is also a significant issue in maize harvest and silage.

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