Effects of moisture content and stem region on the bending characteristics of chickpea stem

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Abstract: This study was conducted with the aim to evaluate the effects of moisture content and stem region on some geometric properties and bending characteristics of chickpea stems including, bending stress and Young's modulus. The experiments were conducted at four moisture contents of 10%, 15%, 20% and 25%, wet basis and at the bottom, middle and top regions of stem. Based on the results obtained, the values of the geometric properties of the stem increased with increasing moisture content and also increased towards the bottom region. The bending stress and Young modulus decreased with increase in the moisture content and increased towards the top regions. The average bending stress was obtained as 28.76 MPa varying from 39.20 to 17.07 MPa, while the average Young's modulus was calculated as 494.48 MPa ranging from 694.75 to 302.54 MPa.

Keywords: chickpea stem, geometric properties, bending stress, Young modulus

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1 Introduction

Chickpea (*Cicer arietnum* L.), an important source of protein and starch, is mainly grown in the hot climates of India, Pakistan, Iran, Ethiopia, Mexico, and the Mediterranean area (Shahbazi, 2011). The chickpea stem is erect, branched, viscous, hairy, trite, herbaceous, green, and solid. Harvesting of chickpeas is currently carried out manually by labourers in a tedious manner and with a low level of efficiency in fallow fields in developing countries (Golpira, 2013). Low yield, irregular and small fields, uneven ripening, low plant stature, and high probability of shattering losses are the challenges of harvesting chickpeas (Golpira, 2013). The physical and mechanical properties of chickpea stems, like those of other plants, are essential for selecting the design and operational parameters of equipment relating to harvesting, threshing, handling and other processing of the stems. The important properties of the cellular material that in cutting are: compression, tension, bending, shearing, density and friction (Yiljep and Mohammed, 2005). These properties are affected by numerous factors such as the species variety, stem diameter, maturity, moisture content and cellular structure (Nazari et al., 2008; Tavakoli et al., 2009). These properties are also different at different heights of the plant stem. Hence, it is necessary to determine the mechanical properties such as the bending and shearing stress and energy requirements for suitable knife design and operational parameters (Ince et al., 2005).

Many studies have been conducted to determine the physical and mechanical properties of plant stems. Skubisz (2001) used a mechanical and an X-ray method to determine the mechanical properties of the stems of winter rape varieties, and found that the character of the changes in the rigidity, bending stress, static shearing energy, and the dynamic shearing energy properties on the length of the stem was best expressed by a quadratic polynomial. Similar results were also reported by Grundas and Skubisz (2008) on rape stem and Skubisz (2002) on pea stem. Chen et al. (2004) found that the

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average values of the maximum force and the total cutting energy for hemp were 243 N and 2.1 J, respectively. Nazari Galedar et al. (2008) reported that the maximum shear strength and shearing energy for alfalfa stem were 28.16 MPa and 345.80 mJ, respectively. Tavakoli et al. (2009) found that the values of the physical properties (major and minor diameter, thickness of stem, cross-section area of wall, second moment of area and mass per unit length) of barley straw increased with increasing moisture content. The physical properties also increased towards the stem third internode position. Esehaghbeygi, Hoseinzadeh, and Masoumet et al. (2009) reported that the bending stress and Young's modulus of canola stems decreased as the moisture content increased while the specific shearing energy increased with increasing the stem moisture content. Similar results were also reported by Shahbazi et al. (2011) on safflower stalk.

Information relating to the physical and mechanical properties of chickpea stem is limited. Therefore, the objective of this study was to investigate the effects of moisture content and stem region on the bending characteristics of chickpea stem in terms of the bending stress and Young's modulus.

2 Materials and methods

The chickpea (*Hashem Variety*) used for the present study is one of the prevalent varieties of chickpea in Iran and was obtained from the farms in the Lorestan province, Iran, during the summer season in 2015. After attaining optimum maturity, the chickpea stem samples were collected and then the pods and the leaves were removed from the stem. The diameter of the chickpea stems decreased towards the top of the plant; therefore, stems showed different physical and mechanical properties at different heights due to the variable cross-sectional area. For this reason, the stems, below primary branch, were equally divided into three regions as top (A), middle (B), and bottom (C) (Figure 1) after removing approximately 10 mm lengths (region D in Figure 1) from the bottom end (from the growth and root region of the stems). The average values for the lengths were found to be 60.32, 65.05 and 70.01 mm for the bottom, middle and top region, respectively. For each region of chickpea stems, its diameter (average diameter at the midpoint) was measured by a digital caliper with an accuracy of 0.01 mm, and then the cross-section area and second moment of area were calculated. Most specimens were circular in cross-section, therefore the second moment of inertia of the cross-sectional area, I (mm^4), was calculated as:

$$I = \frac{\pi d_s^{\ 4}}{64} \tag{1}$$

where, d_s is the stem diameter (mm).

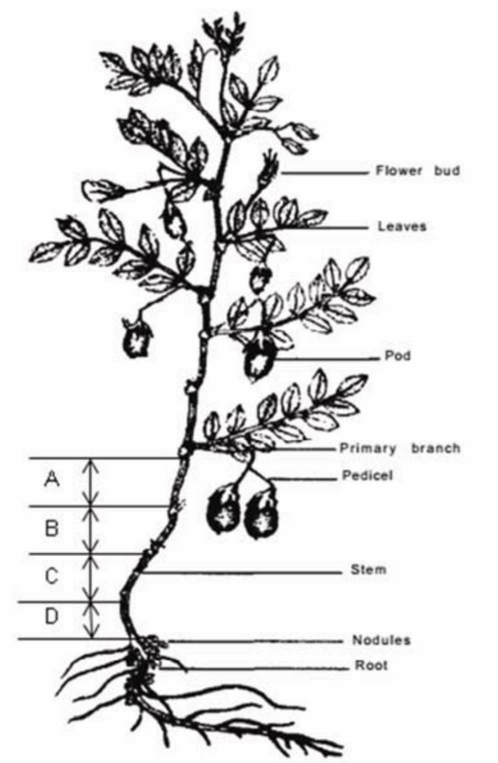

Figure 1 Diagram of chickpea stems identifying regions: (A) top region, (B) middle region, (C) bottom region and (D) woody region

ASABE 358.2DEC 98 was used to determine the average moisture content of the chickpea stems (ASABE, 2008). The initial moisture content of the specimens was determined to be 8.99% (wet basis). Specimen samples with higher moisture contents were prepared by adding calculated amounts of distilled water to wet the specimens which were sealed in separate polyethylene bags and kept at 5°C in a refrigerator for a week to enable the moisture to distribute 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 (Tavakoli et al., 2009). The specimens were then reweighed to specify the amounts of water absorbed by them. The experiments were conducted at moisture levels of 10%, 15%, 20% and 25% w.b. The field measurements showed that the chickpea stem moisture content was in the range of 15% to 25% (w.b), at the harvesting time (not published data).

In this study, the bending forces were measured and the bending stress and the Young's modulus were calculated from these data are similar to those described by other researchers (Nazari Galedar et al., 2008; Tavakoli et al., 2009; Shahbazi et al., 2011). The mechanical properties of chickpea stems were assessed using a proprietary tension/compression testing machine (Instron Universal Testing Machine /SMT-5, SANTAM Company, Tehran, Iran) is similar to those described by Nazari Galedar et al. (2008), Tavakoli et al. (2009), Shahbazi and Nazari Galedar, (2010), Shahbazi et al. (2011) and Shahbazi (2012) (Figure 2). To determine the bending stress and Young's modulus in bending, a three-point loading apparatus was used (Figure 3). The specimens were placed on the two rounded metallic supports 50 mm apart, and the force was applied to the center of the stem with the loading rate of 10 mm min^{-1} using a loading plate driven by the movable support of the tension/compression testing machine (Tavakoli et al. 2009; Shahbazi et al., 2011; Amirian et al., 2017). Force versus deformation data were recorded by the computer until sample fracture, then force-deformation curves was obtained from the test data using the software (Figure 4). The bending force and deformation at the bio yield peak and at the inflection point were obtained from all curves (point A, Figure 4).

The bending stress (the maximum stress in a homogeneous bar deformed by pure bending), σ_b (MPa), was calculated by the following equation (Nazari Galedar et al., 2008; Tavakoli et al., 2009):

$$\sigma_b = \frac{F_b y l}{4I} \quad (2)$$

where, F_b = the bending force (N); y = distance of outermost fibre from the neutral axis ($y= d_s/2$) (mm); l = distance between the two metal supports (50 mm).

The Young modulus, E (MPa), of chickpea stem was calculated from the following expression for a simply supported beam located at its centre (Tavakoli et al., 2009):

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

where, δ is the deflection at the specimen centre (mm).

In this study, the effects of stem moisture content (at: 10%, 15%, 20% and 25% wet basis) and stem region (at: top, middle and bottom regions) on the bending characteristics of chickpea stems were studied. A factorial test with two factors (moisture content and stem region) and three replications for bending characteristics and 20 replications for geometric properties with the base of completely randomized experimental design were used in this study. 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 software (vers. 15, SPSS, Inc., Chicago, IL, USA).

Figure 2 Tension/compression testing machine for the measurement the mechanical properties of chickpea stems (Instron Universal Testing Machine /SMT-5, SANTAM Company)

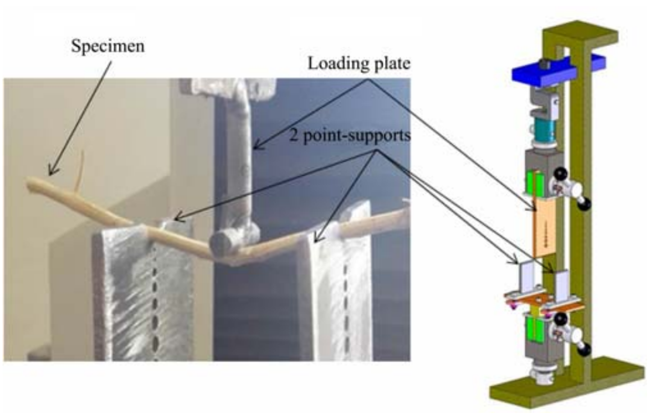

Figure 3 Apparatus (three-point loading) for the measurement of bending characteristics of chickpea stems

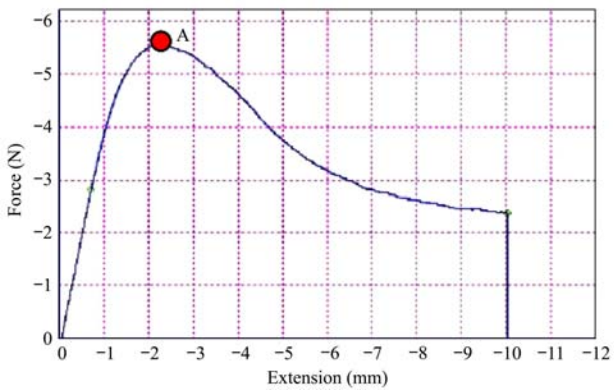

Figure 4 Typical force-deformation of bending characteristics of chickpea stem

3 Results and discussion

3.1 Geometric properties

The variance analysis of the data indicated that the effects of the moisture content, stem region and the interaction between moisture content and stem region had significant effects on the all geometric properties (stem diameter, cross-section area of stem, and second moment of area) of the chickpea stem at 1% probability level (P<0.01) (Table 1). The mean values for the geometric properties (stem diameter, cross-section area of stem, and second moment of area) of the chickpea stem at different moisture content and stem region presented in Table 2. It is evident from Table 2 that as the moisture content of the stem increased the geometric properties are generally increased. Similar results were also reported by Annoussamy et al. (2000) for wheat straw, Shahbazi et al., 2011 for safflower stalk and Nazari Galedar et al. (2008) for alfalfa stem. With increasing moisture content of chickpea stems from 10% to 25% the mean value of their diameter increased by 1.6 times (from 3.57 cm to 5.78 cm).

The geometric properties of chickpea stem also increased towards the bottom region of the stem (Table 2). The values of all geometric properties studied at the bottom, middle and top stem regions had significant differences (P<0.05). Similar increasing trends 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, Nazari Galedar et al. (2008) for alfalfa stem, Tavakoli et al. (2009) for barley straw, and Shahbazi et al. (2011) for safflower stalk.

Table 1 Results of analyses of variance (Mean Square Error) for the geometric properties of the chickpea stem

Source	Dependent Variable	Df	Mean Square	F value
Moisture content (M)	Stem diameter	3	49.444	39.298**
	Cross-section area	3	4703.643	45.234**
	Second moment of area	3	234174.176	33.561**
Stem region (R)	Stem diameter	2	247.338	196.585**
	Cross-section area	2	18401.060	176.961**
	Second moment of area	2	513232.883	73.556**
M × R	Stem diameter	6	17.448	13.868**
	Cross-section area	6	2499.176	24.034**
	Second moment of area	6	182023.224	26.087**
Error	Stem diameter	228	1.258	
	Cross-section area	228	103.984	
	Second moment of area	228	6977.470	

Note: **-Significant at 1% level.

Table 2 Effects of moisture content and stem region on the geometric properties of the chickpea stem

Independent variable		Geometric property		
		d_S (mm)	A (mm^2)	I (mm^4)
Moisture content (%)	10	3.57 c*	11.37 c	15.54 b
	15	4.60 b	18.91 b	42.18 b
	20	4.78 b	19.57 b	42.27 b
	25	5.78 a	32.68 a	155.48 a
Stem region	Bottom	6.67 a	37.93 a	155.56 a
	Middle	4.06 b	14.31 b	23.29 b
	Top	3.32 c	9.65 c	11.69 c

Note: *- a– c-means followed by different letters are significantly different from other in the same column (P<0.05). d_s- stem diameter, A– cross-section area of stem, I– second moment of area.

3.2 Bending characteristics

3.2.1 Bending stress

The variance analysis of the data indicated that the moisture content and the stem region had significant effects on the bending stress of the chickpea stem at 1% and 5% probability levels, respectively. The effect of interaction between moisture content and stem region on the bending stress was not significant (P>0.05) (Table 3). The results of Duncan's multiple range tests for comparing the mean values of the mechanical properties of the chickpea stem at different moisture contents and stem regions are presented in Table 4. It is evident from Table 4 that as the moisture content of the stem increased, the bending stress of chickpea stems decreased, indicating a reduction in the brittleness of the stem. Similar results were also reported by Annoussamy et al. (2000) for wheat straw, Ince et al. (2005) for sunflower stalk and Nazari Galedar et al. (2008) for alfalfa stem. With increasing moisture content of chickpea stems from 10% to 25% the mean value of their bending stress decreased by 2.29 times (from 39.20 to 17.07 MPa). The average values for the bending stress were found to be 17.07, 27.44, 31.35 and 39.20 MPa for moisture contents of 25%, 20%, 15% and 10% w.b., respectively. According to Duncan's multiple range test results, the difference between the effects of moisture content at the level of 25% with all other levels and between 20% and 10% was significant on the bending stress at 5% probability level, while there was no significant difference between the effect of moisture contents of 10% and 15%, and 15% and 20% (Table 4). The bending stress of chickpea stems increased towards the top region of the stem (Table 4). Similar results have been reported by other researchers (Ince et al., 2005; Nazari Galedar et al., 2008; Tavakoli et al., 2009). The bottom region had about 64.91% lower value of bending stress than the top region (from 35.39 to 21.47 MPa). According to Duncan's multiple range test results, the bending stress mean value at bottom region was statistically different from the middle and top regions (P<0.05).

Table 3 Results of analyses of variance (Mean Square Error) for the bending properties of the chickpea stem

Source	Dependent Variable	Df	Mean Square	F value
Moisture content (M)	Bending stress	3	762.032	11.007**
	Young's modulus	3	243901.834	20.376**
Stem region (R)	Bending stress	2	586.110	8.466*
	Young's modulus	2	465771.856	38.912**
M × R	Bending stress	6	3.192	0.046 ns
	Young's modulus	6	14891.835	1.244 ns
Error	Bending stress	24	69.229	
	Young's modulus	24	11969.779	

Note: **-Significant at 1% level. *- Significant at 5% level. ns- Not significant.

Table 4 Effects of moisture content and stem region on the bending properties of the chickpea stem

Independent variable		Mechanical property	
		σ_b (MPa)	E (MPa)
Moisture content (%)	10	39.20 a	694.75 a
	15	31.35 ab	536.79 b
	20	27.44 b	443.84 b
	25	17.07 c	302.54 c
Stem region	Bottom	21.47 b	281.83 c
	Middle	29.44 a	530.81 b
	Top	35.39 a	670.79 a

Note: *- a– c-means followed by different letters are significantly different from other in the same column (P<0.05). σ_b-bending stress, E- oung modulus.

In Figure 5 the bending stress is plotted against the moisture content, for each stem region. The figure reveals that, at all the stem regions considered, the bending stress decreases as the moisture content increases. Its mean values decreased from 46.21 to 23.05, 40.37 to 17.06 and 30.82 to 11.11 MPa for the top, middle and bottom regions, respectively, as the moisture contents increased from 10% to 25%. Regression analysis was used to find and fit the best general models to the data. The results showed that as the moisture content of the stem increased, the bending stress decreased as a polynomial, so the dependence of bending stress of chickpea stems (σ_b, MPa) on the stem moisture content (M, %) was expressed by the following best-fit equations for each stem region:

$$\sigma_b = -0.028M^2 - 0.474M + 53.27 \quad R^2=0.979$$

for: Top region (4)

$$\sigma_b = -0.029M^2 - 0.430M + 46.77 \quad R^2=0.995$$

for: Middle region (5)

$$\sigma_b = -0.020M^2 - 0.584M + 38.45 \quad R^2=0.9939$$

for: Bottom region (6)

All the indexes are significant at the level of 99.99%.

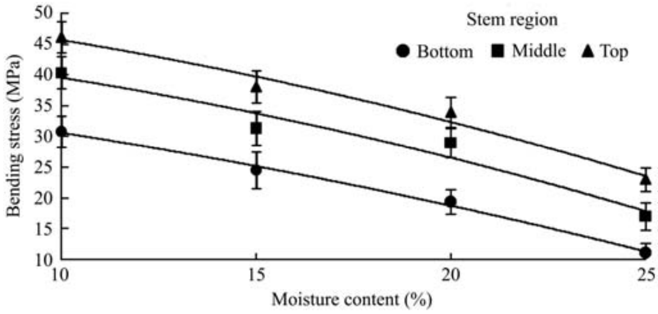

Figure 5 The changes of bending stress of chickpea stems with moisture content according to the stem regions

3.2.2 Young's modulus

Effects of moisture content and stem region on the Young's modulus of the chickpea stem in bending were also evaluated in this study. Both the moisture content and region of stem significantly affected Young's modulus of chickpea stems at 1% level of confidence (P<0.01). The interaction effect of moisture content and stem region on the Young's modulus was not significant (P>0.05) (Table 3). Results revealed that the Young's modulus of chickpea stems was also decreased with increasing moisture content, and increased from the bottom of the stem to the top (Tables 4). Similar results were also reported by O'Dogherty et al. (1995), Ince et al. (2005), Nazari Galedar et al. (2008) and Tavakoli et al. (2009). The average values of the Young modulus varied from 694.75 to 302.54 MPa, when the moisture content changed from its lowest value to its highest amount in this study (Table 4). According to the Duncan multiple range tests, the Young modulus was found to be significantly higher (P<0.05) for the three lowest moisture contents (10%, 15% and 20%), with a mean value of 558.46 MPa. This is compared with a mean value of 302.54 MPa for the other moisture content (25%). The average values for the Young modulus were found to be 281.83, 530.81 and 670.79 MPa for the bottom, middle and top region, respectively. Ince et al. (2005) reported the bending stress and Young's modulus for sunflower stalk as 37.7 to 62.09 MPa and 1251.28 to 2210.89 MPa, respectively. Esehaghbeygi, Hosseinzadeh, and Khazaei et al. (2009) evaluated the bending stress and modulus of elasticity for wheat stem. They reported that bending stress and modulus of elasticity increased as the moisture content decreased and decreased as the cutting height of stem increased. The average of bending stress varied between 17.74-26.77 MPa and modulus of elasticity varied between 3.13-3.75 GPa. Chattopadhyay and Pandey (1999) determined the bending stress for sorghum stalk as 40.53 and 45.65 MPa at the seed stage and forage stage, respectively. There were no studies on bending strength and Young's modulus of chickpea stems.

The higher values of Young modulus were found at the top region due to the smaller stem diameter in this region. The Young modulus mean value at top region was statistically different from the middle and bottom regions (P<0.05).

Figure 6 shows the variation of the chickpea stems Young modulus with the moisture content at each stem region. As follows from the relations presented in the figure, for all the stem regions considered, the Young modulus of stems decreased with increase in their moisture content. The highest Young modulus value was obtained as 938.47 MPa in the top region at a moisture content of 10%, while the lowest value was found to be 188.92 MPa in the bottom region at a moisture content of 25%. Regression analysis showed that the Young modulus decreased as a polynomial with increasing moisture content at all regions. The relationship between the chickpea stem Young modulus (E, MPa) and moisture content (M, %) at each stem region can be expressed by the following best-fit regression equations:

$$E = -0.053M^2 - 32.56M + 1258.01 \quad R^2=0.984$$

at: Top region (7)

$$E = 0.024M^2 - 29.01M + 103.02 \quad R^2=0.999$$

at: Middle region (8)

$$E = 0.527M^2 - 32.09M + 665.30 \quad R^2=0.989$$

at: Bottom region (9)

All the indexes are significant at the level of 99.99%.

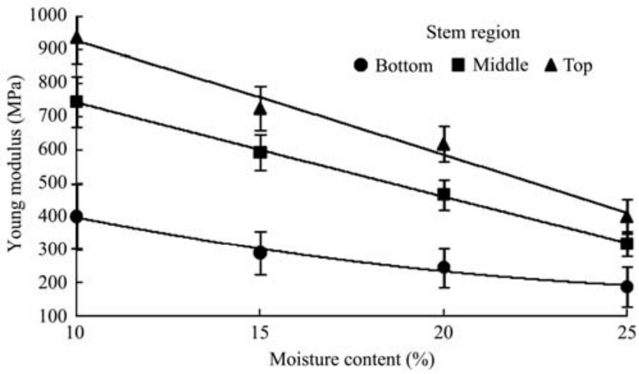

Figure 6 The changes of Young's modulus of chickpea stems with moisture content according to the stem regions

4 Conclusions

The following conclusions are drawn from the investigation of the effects of the moisture content and stem region position on the geometric properties, bending stress and Young's modulus of chickpea stem. The values of the geometric properties of chickpea stem increased with increasing moisture content and towards the bottom region. The results showed that there was a big difference between the highest and the lowest moisture contents, also between top and bottom regions in terms of bending stress and Young modulus. Both the bending stress and Young's modulus decreased with an increase in the moisture content and towards the bottom region of the stem. The bending stress varied from 39.20 to 17.07 MPa and the Young's modulus ranged from 694.75 to 302.54 MPa. The bending stress of chickpea stem decreased from 46.21 to 23.05, 40.37 to 17.06 and 30.82 to 11.11 MPa for the top, middle and bottom regions, respectively, as the moisture contents increased from 10% to 25%. The Young's modulus of the stem also varied from 938.47 to 400.48, 744.64 to 318.23, and from

401.13 to 188.93 MPa for the top, middle and bottom regions, respectively, at different moisture contents studied.

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