Effects of moisture content and level in the crop on the shearing properties of chickpea stem

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Abstract: The objective of this study was to determine the effects of moisture content and stem region on some physical and shearing properties of chickpea stems. The experiments were conducted at four moisture contents of 10%, 15%, 20% and 25% w.b. and at the bottom, middle and top regions of stem. For measuring the shearing forces, the stem specimens were severed by using a computer aided cutting apparatus. The shearing energy was calculated by using the area under the shearing force versus displacement curve. Based on the results obtained, the values of the stem physical properties increased with the increasing moisture content. Their values also increased towards the bottom region. The shearing stress and the specific shearing energy also increased with the increasing moisture content. Their values also increased towards the bottom region of the stem due to the structural heterogeneity. The maximum shear stress and specific shearing energy were found to be 17.26 MPa and 34.81 mJ mm^{-2}, respectively, and both occurred at the bottom region with the moisture content of 25% w.b.

Keywords: chickpea stem, shearing stress, specific shearing energy

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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 properties of the cellular material which are important 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 Galedar 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

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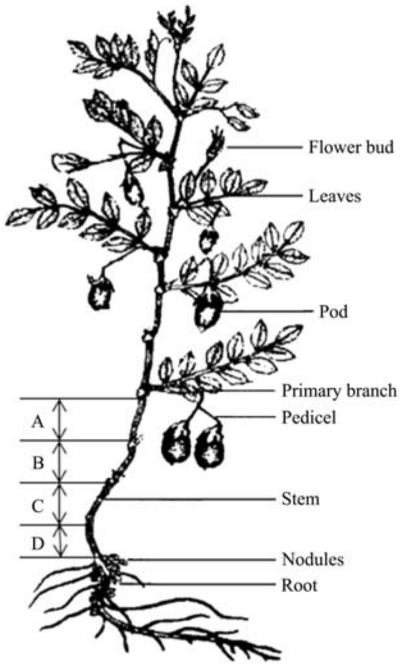
Grundas and Skubisz (2008) on rape stem and Skubisz (2002) on pea stem. Chen et al. (2004) found that the average values of the maximum force and the total cutting energy for hemp were 243 N and 2.1 J, respectively. Nazari Galedar et al. (2008) reported that the maximum shear strength and shearing energy 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 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.

However, detailed measurements of engineering properties of chickpea stem and variations in physical and mechanical properties at various levels of moisture content and stem region have not been investigated. Therefore, the objective of this study was to investigate the effects of moisture content and stem region on some geometric properties, namely: stem average diameter, stem cross-sectional area and second moment of area and some mechanical properties, namely: shearing stress and specific shearing energy of chickpea stems.

2 Materials and methods

The chickpea (var. *Arman*) 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, stem shows different physical and mechanical properties at different heights due to the variable cross-sectional areas. 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). For each stem specimen, its diameter (average diameter at the midpoint) was measured, and then the cross-section area and second moment of area were calculated.



Note: A. top region, B. middle region, C. bottom region and D. woody region.

Figure 1 Diagram of chickpea stems identifying regions:

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 stored in a cold store at 5ºC for 10 days (Tavakoli et al., 2009). Before starting each test, the required amounts of stems were allowed to warm up to room temperature. 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.

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) 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). The shear stress was measured in double shear using a shear box (Figure 2) consisting of two fixed parallel hardened steel plates spaced 5 mm apart, between which a third plate can slide freely in a close sliding fit. A series of holes with were drilled through the plates to accommodate the stems of differing diameter. Shear force was applied to the stem specimens by mounting the shear box on the tension/ compression testing machine. A few idle runs without stems were also performed before running the main testes to account and eliminate the influence of the frictional resistance between the sliding plate and fixed plates of shear apparatus on the experimental values. The sliding plate was loaded at a rate of 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 specimen failure. The shear failure stress (or ultimate shear strength), τ_s (MPa), of the specimens was calculated from the following Equation:

$$\tau_s = \frac{F_S}{2A} \tag{1}$$

where, F_s is the shear force at failure (N); and A is the cross-sectional area of the stem at shearing plane (mm^2).

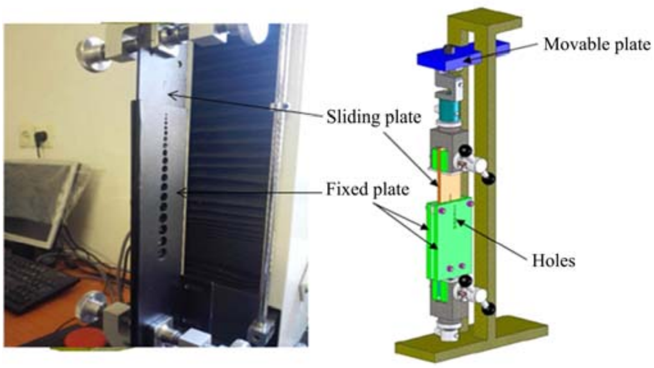


Figure 2 Apparatus for measurement of shearing stress of chickpea stem

The shearing energy was calculated by using the area under the curves of shear force and displacement (Chen et al., 2004). For this case, the area under the curve was divided into the basic geometrical shapes and the area was calculated using the force and displacement data and a standard computer program (version 5, SMT Machine Linker, software, SANTAM Company, Tehran, Iran). The specific shearing energy, E_{sc} (mJ mm^{-2}), was found by the following Equation:

$$E_{sc} = \frac{E_s}{A} \tag{2}$$

where, E_s is the shearing energy (mJ).

In this study, the effects of stem moisture contents (at: 10%, 15%, 20% and 25% wet basis) and stem regions (at: top, middle and bottom regions) on the physical and mechanical properties of chickpea stems were studied. A factorial test with two factors and 20 replications 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 15 software.

3 Results and discussion

3.1 Geometric properties

The mean values for the geometric properties of the chickpea stem are presented in Table 1. The moisture content had little effect on the geometric properties of chickpea stem. As the increase of moisture content, the geometric properties generally increased. The effects of moisture content on the stem average diameter, stem cross-sectional area and second moment of area were not significant at 5% probability level. The geometric properties also increased towards the bottom region of the stem. 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 wheat straw, and Shahbazi et al. (2011) for safflower stalk.

Table 1 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	4.02 c*	12.67b	12.81 b
	15	5.04 b	19.86 a	31.41 ab
	20	5.36 ab	22.55 a	40.49 a
	25	6.01 a	28.37 a	64.09 a
Stem region	Bottom	7.06 a	39.13 a	121.89 a
	Middle	5.10 b	20.34 b	32.93 b
	Top	4.12 b	13.32 b	14.14 b

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

3.2 Shearing properties

3.2.1 Shearing Stress

The shearing stress of the chickpea stem was evaluated as a function of moisture content and stem region. The moisture content and stem region had significant effects on the bending stress at 1% probability level (Table 2). The interaction effect of moisture content and stem region on the bending stress was not statistically significant (P>0.05).

Table 2 Results of analyses of variance (Mean Square Error) for the shearing properties of the chickpea stem

Source	Dependent Variable	Df	Mean Square	F value
Moisture content (M)	Shearing stress	3	195.204	34.150**
	Specific shearing energy	3	308.740	15.215**
Stem region (R)	Shearing stress	2	94.743	16.575**
	Specific shearing energy	2	503.716	24.824**
M × R	Shearing stress	6	3.893	0.681 ns
	Specific shearing energy	6	23.965	1.181 ns
Error	Shearing stress	24	5.716	
	Specific shearing energy	24	20.292	

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

The shearing stress of the chickpea stems increased with the increase of moisture content (Table 3). Similar results were also reported by most previous researchers (Annoussamy et al., 2000; Nazari Galedar et al., 2008; Tavakoli et al., 2009). The average values for the shearing stress varied from 3.18 to 13.29 MPa, by increasing the moisture content from 10% to 25%, showing that the shearing stress at the highest moisture content was approximately four times higher than that of the lowest moisture content. In addition, according to the Duncan multiple range tests, the values for the shearing stress were completely different for the distinct moisture contents, but only at moisture contents less than 20%; there were no statistically significant differences at moisture contents of higher than 20% (Table 3).

From Table 3, it is seen that shearing stress decreased when moving from the bottom of the stems to the top. This result had a good correlation with the results reported by Ince et al. (2005), and Nazari Galedar et al. (2008). The average values for the shearing stress were found to be 11.54, 8.10, and 5.90 MPa for the bottom, middle, and top regions, respectively (Table 3). The chickpea stem has a hard structure because of the high cellulose content. The top regions of plant stem have the lowest amount of cellulose (Annoussamy et al., 2000). Therefore, the shearing stress of the bottom region is higher than that of the middle and top regions of the stem. In addition, according to the Duncan's multiple range tests, the values for the shearing stress were completely different for the distinct stem regions (Table 3).

Table 3 Effects of moisture content and stem region on the shearing properties of the chickpea stem

Independent variable		Shearing property	
		τ_s, MPa	E_{sc}, mJ mm^{-2}
Moisture content, %	10	3.18 c	9.83 c
	15	6.73 b	12.39 bc
	20	11.81 a	15.18 b
	25	13.29 a	23.33 a
Stem region	Bottom	11.54 a	22.11 a
	Middle	8.10 b	14.16 b
	Top	5.92 c	9.28 c

Note: *- a– c-means followed by different letters are significantly different from other in the same column (P<0.05), τ_s – shearing stress, and E_{sc} – specific shearing energy.

Figure 3 presented the relationship between the shearing stress and moisture content for all the stem regions. As moisture content of the stem increased, the shearing stress increased in all the regions (Figure 3). In Figure 3, the greatest shearing stress was obtained as 17.26 MPa in the bottom region at the moisture content of 25% of stem, while the lowest shearing stress was found to be 1.61 MPa in the top region at a moisture content of 10%. The shearing stress decreased towards the top region of the stem in all the moisture contents. The differences in the values for the shearing stress in the intermediate stem regions also diminished as the moisture content decreased. It was found that the shearing stress of chickpea stems increased as a polynomial function of their moisture content for all the regions. The following relationships were found between the shearing stress (τ_s, MPa) and moisture content (M, %), for each stem region:

$$\tau_s = -0.028M^2 + 1.510M - 10.93 \quad R^2 = 0.985 \quad \text{for: Top region} \tag{3}$$

$$\tau_s = -0.016M^2 + 1.328M - 9.018 \quad R^2 = 0.970 \quad \text{for: Top region} \tag{4}$$

$$\tau_s = -0.017M^2 + 1.451M - 7.982 \quad R^2 = 0.994 \quad \text{for: Top region} \tag{5}$$

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

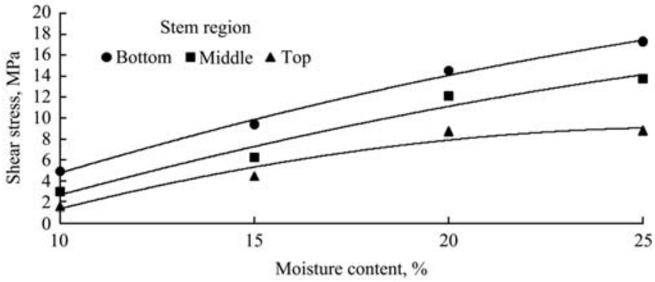


Figure 3 The changes of shear stress of chickpea stems with moisture content according to the stem regions

3.2.2 Specific shearing energy

The values of the specific shearing energy of the chickpea stem were significantly affected by moisture content and stem region ($P<0.01$). However, the interaction effect of moisture content and stem region on the specific shearing energy was not statistically significant ($P>0.05$) (Table 2). The specific shearing energy requirement increased with increasing stem moisture content (Table 3). This effect of moisture content was also reported by Annoussamy et al. (2000) for wheat straw, Chen et al. (2004) for hemp stem, Ince et al. (2005) for sunflower stem, and Nazari Galedar et al. (2008) for alfalfa stem. The mean values of specific shearing energy varied from 9.93 to 23.33 mJ mm^{-2} when moisture content changed from 10 to 25% (Table 3). The reason for this difference may be expressed as the viscous damping effect of moisture.

The specific shearing energy decreased towards the top region of the stem (Table 3). The specific shearing energy values varied from 5.61 to 14.98, 9.90 to 20.21, and 13.99 to 34.81 mJ mm^{-2} for the top, middle and bottom regions, respectively, at the different moisture contents that were studied in this research. This energy was greater in the bottom regions because of the accumulation of more mature fibres in the stem (Ince et al., 2005). According to the Duncan multiple range test results, these values were different from each other for the distinct stem regions, but the effect of moisture content was only significant at above 20% (Table 3).

Figure 4 showed the variation of specific shearing energy with moisture content for all the stem regions. The values of the interaction between moisture content and stem region on the specific shearing energy (Figure 4), varied from 5.61 to 34.81 mJ mm^{-2}. The minimum shearing energy (5.61 mJ mm^{-2}) obtained for the top region with the lowest moisture content (10%), and the maximum shearing energy (34.81 mJ mm^{-2}) obtained for the bottom region with the highest moisture content (25%). The models fitted to the data using the regression technique showed that the specific shearing energy increased a polynomial function with the increase of moisture content for all stem regions. Thus, the following equations were found for the relationship between specific shearing energy (E_{sc}, mJ mm^{-2}) of the chickpea stems and moisture content (M, %), at each stem region:

$$\tau_s = 0.040M^2 - 0.825M + 10.02 \quad R^2=0.984$$
for: Top region (6)

$$\tau_s = 0.035M^2 - 0.590M + 12.44 \quad R^2=0.997$$
for: Middle region (7)

$$\tau_s = 0.091M^2 - 1.856M + 23.74 \quad R^2=0.990$$
for: Bottom region (8)

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

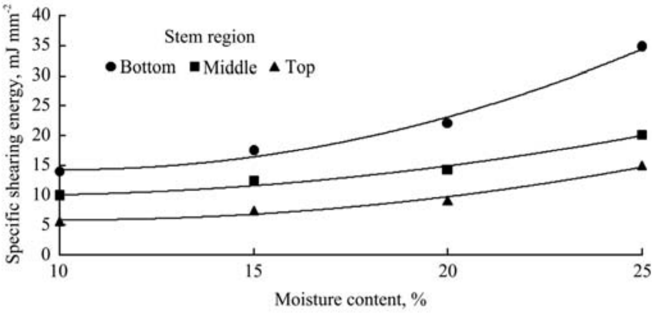


Figure 4 Variation of specific shearing energy of chickpea stems with moisture content according to the stem regions

4 Conclusions

The values of the physical properties of chickpea stem increased with the increase of moisture content. The physical properties also increased towards the bottom region. The results showed that an increase in moisture content of chickpea stem led to an increase in the shear stress and specific shearing energy. The average values of the shearing stress and specific shearing energy varied from 3.18 to 613.29 MPa and 9.83 to 23.33 mJ mm^{-2}, respectively, as the moisture content increased from 10% to 25%. For all moisture contents that were studied, the shearing stress and specific shearing energy decreased from the bottom towards the top region of the stem. There was a big difference between the highest and the lowest moisture contents in terms of shearing stress and specific shearing energy. This result indicates that harvesting chickpea stem at lower moisture contents can be recommended to minimise the shearing force and shearing energy requirements. Additionality, the effect of cutting height is very important for reducing shearing force and energy.

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