Tensile strength of safflower stalk as affected by moisture content, stalk region and loading rate

Feizollah Shahbazi

(*Lorestan University*, *Khoram abad*, *Lorestan*, *I.R. Iran*)

Abstract: Information on the physical and mechanical properties of safflower stalk is important for the design of machines such as mowers, balers and choppers. The research was conducted to determine tensile strength of safflower stalk as a function of moisture content, stalk region, and loading rate. The experiments were conducted at four moisture contents (9.98, 17.85, 26.37 and 38.75% w.b), three stalk regions (bottom, middle, and top), and three loading rates (5, 10 and 20 mm min^{-1}). Based on the results obtained, the average tensile strength of safflower stalks, at different test conditions, was obtained as 32.31 MPa varying from 11.63 to 87.84 MPa. The tensile strength decreased as polynomial with the increasing moisture content and towards the top regions. The tensile strength decreased from 46.79 to 26.56 MPa, 44.16 to 26.16 MPa, and 38.32 to 19.27 MPa for the bottom, middle and top regions respectively, as the moisture content increased from 9.98% to 38.75%. The tensile strength increased linearly with the increase in the loading rate for all the regions. Its values increased from 28.98 to 43.98 MPa, from 23.31 to 32.45 MPa in the bottom and top regions respectively, as the loading rate increased from 5 to 20 mm min^{-1}.

Keywords: safflower stalk, tensile strength, height region, moisture content, loading rate

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1 Introduction

Safflower (*Carthamus tinctorius* L.), which belongs to the Composite family, is cultivated in several parts of the world due to its adaptability to different environmental conditions (Baumler et al., 2006; Sacilik et al., 2007). It is a rich source of oil (35%-40%) and linoleic acid content (75%-86%). The safflower oil is of multi-purpose used especially as bio-diesel for the production of fuel for internal combustion engines. The safflower production has recently increased due to increasing research works about alternative energy sources. The estimated planting area of safflower in the world was about 814,000 ha in 2005 (FAO, 2006). Safflower cultivated area has increased in the last few years in Iran so that its cultivated area reached to 15,000 ha in 2005-2006 (Pourdad et al., 2008). The average seed yield of safflower is about 900 kg ha^{-1} in Iran (Pourdad et al., 2008). Safflower is a highly branch, usually with many long sharp spines on the leaves, and is sometimes spineless. Plants are 600 to 1200 mm tall with globular flower heads and commonly brilliant yellow, orange, or red flowers.

The physical and mechanical properties of safflower stalks, like those of other plants, are essential for the selecting design and operational parameters of equipment related to harvesting, threshing, handling and other processing operations of the stalks. The properties of the cellular material that are important in cutting are compression, tension, bending, shearing, density and friction (Yiljep and Mohammed, 2005; Shaw and Tabil, 2006). These properties are affected by numerous factors such as the species variety, stalk diameter, maturity, moisture content and cellular structure (Nazari et al., 2008a, b; Tavakoli et al., 2009). These properties

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Corresponding author: Feizollah Shahbazi, Email: shahbazi.f@lu.ac.ir.

are also different at different heights of the plant stalk. Hence, it is necessary to determine the mechanical properties such as the tensile strength, the bending and shearing stress, and energy requirements for suitable knife design and operational parameters (Ince et al., 2005). In a study Skubisz (2001) used a mechanical and an X-ray method for the determination of the mechanical properties of the stems of winter rape varieties, and found that the character of the changes in the mechanical properties on the length of the stem is described by a square polynomial. Similar results were also reported by Skubisz (2002) on pea stem and Grundas and Skubisz (2008) on rape stem. Chen et al. (2004) found that the average values of the maximum force and the total cutting energy for hemp stem were 243 N and 2.1 J, respectively. Nazari et al. (2008a) reported that for the alfalfa stem, the maximum shear strength and shearing energy were 28.16 MPa and 345.80 MJ, respectively. Esehaghbeygi et al. (2009) reported that the specific shearing energy of canola stem increased, but the bending stress and modulus of elasticity decreased as the moisture content increased. Nazari et al. (2009) reported the tensile strength of alfalfa stems increased exponentially with decrease in the moisture content and towards the lower regions. They also found that the tensile strength increased linearly with increases in the rate of loading for all the regions. Tavakoli et al. (2009) found that the values of the physical properties of barley straw increased with the increasing moisture content. They also found that the physical properties also increased towards the third internodes position.

There are no studies on the influence of moisture content, stalk region, or loading rate on tensile strength of safflower stalks. Therefore, the objective of this study was to measure the tensile strength of safflower stalk and to determine the relationship between that and the moisture content, stalk region, and loading rate.

2 Materials and methods

The safflower stalk (cv. *Dincer*) used for the present study was one of the prevalent varieties of safflower in Iran and was obtained from the farms in Lorestan province, Iran, during the summer season in 2011. After attaining optimum seed maturity, the safflower stalk samples were collected and then the flowers and leaves were removed. The diameter of the safflower stalk decreases from the bottom of the plant to the top shows different physical and mechanical properties at different heights due to the variable cross sectional area. For this reason, the stalks were equally divided into three regions as top (A), middle (B), and bottom (C) (Figure 1) after removing 40 mm (region D in Figure 1) from the bottom end (this part is usually left on the field at the harvesting time). Diameter of each sample (average diameter at the midpoint) was measured using an electronic digital caliper (GUANGLU, China) having a resolution of 0.01 mm before starting the tests.

ASAE standard (358.2 DEC 98) was used to determine the average moisture content of the safflower stalks (ASAE standards, 2008). The initial moisture content of the specimens was determined to be 9.98% (w.b). The samples with higher moisture contents were prepared by adding calculated amounts of distilled water to the samples that were sealed in the separate polyethylene bags and stored in a climate controlled storage at 5℃ for 10 days (Tavakoli et al., 2009). Before starting each test, the required amounts of stalks were allowed to warm up to the room temperature. The experiments were conducted at moisture levels of 9.98%, 17.85%, 26.37% and 38.75% (w.b). The field measurements showed that safflower stalk moisture content was in the range of 20% to 30% (w.b), at the harvesting time.

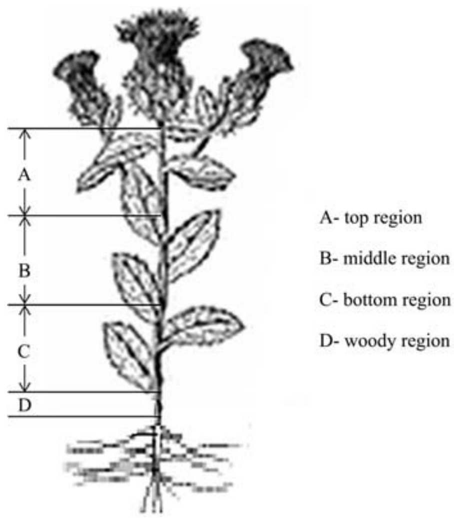
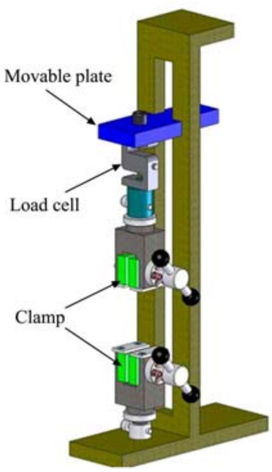


Figure 1 Diagram of safflower stalk identifying regions

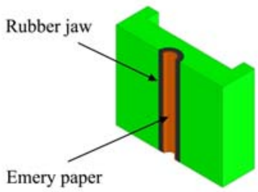
The mechanical properties were measured in the elastic phase immediately after loading, and the strength measurements were made using a materials testing machine at a relatively low strain range. These methods were similar to those reported in most of the literature concerned with such work *e.g* Nazari et al. (2009). Measurement of the tensile strength of forage stems proved difficult because the brittle nature of the straw caused it to fail at the clamps at each end of a specimen when a tensile force was applied. A mechanical device was developed (Figure 2) in which short length of steel rod was then gripped by rubber jaws which had emery paper inserts interposed between the rubber and the specimen (Nazari et al., 2009). The rubber was mounted in steel clamps which could be rapidly clamped to the specimens. Tension was applied to the specimens by mounting the holding clamps in a proprietary tension-compression universal testing machine (Santam, SMT-5, Iran). Three loading rates were used for each experiment. These rates were 5, 10, 20 mm min^{-1}. The tension force was measured by a strain gauge load cell and a force-time record was obtained up to the failure of the specimen. About half of the specimens fractured near the centre of the stem and were acceptable for evaluating the tensile strength. The tensile failure stress (or ultimate tensile strength), σ_t (MPa), of the specimen was calculated by the following equation (Nazari et al., 2009):

$$\sigma_t = \frac{F_t}{A} \tag{1}$$

where, F_t is the tension force at failure, N; and A is the wall area, mm^2.



a. Schematic of apparatus



b. Clamp

Figure 2 Apparatus for the measurement of tensile strength

In this study, the effects of stalk moisture content (at: 9.98%, 17.85%, 26.37% and 38.75% w.b), stalk region (at: top, middle and bottom regions) and loading rate (at: 5, 10 and 20 mm min^{-1}) were studied on the tensile strength of safflower stalks. The factorial experiment was conducted as a randomized design with 12 replicates. Experimental data were analyzed using analysis of variance (ANOVA) and the means were separated at the 5% probability level applying Duncan's multiple range tests in SPSS 17 software.

3 Results and discussion

The average diameter of the sample stalks used in this study, in the top, middle and bottom regions, varied between 3.62 to 5.01, 4.64 to 5.77 and 5.28 to 6.87 mm respectively, at different moisture contents studied. The data obtained from this study showed that the tensile strength of safflower stalks was revealed at different levels of moisture content, stalk region and loading rate. The variance analysis of the data (Table 1) indicated that moisture content, stalk region, and loading rate created a significant effect on the tensile strength of safflower stalk (P<0.01). The average tensile strength at different test conditions was obtained as 32.38 MPa varying from 11.63 to 87.84 MPa. Based on the statistical analysis, the interaction effects of moisture content × loading rate significantly influenced the tensile strength of safflower stalks, at 1% probability level. The interaction effects of the stalk region × loading rate and moisture content × stalk region × loading rate, significantly influenced the tensile strength, at 5% probability level, respectively. Meanwhile, the interaction effect of the moisture content × stalk region was not significant for the tensile strength of safflower stalk (P>0.05) (Table 1).

The results of Duncan's multiple range tests for comparing the mean values of the tensile strength of safflower stalks at different moisture contents, stalk regions, and loading rates are presented in Table 2. It is evident from Table 2 that as the moisture content of the stalk increased, the tensile strength decreased, indicating a reduction in the brittleness of the stalk. Similar results were also reported by Annoussamy et al. (2000) for wheat straw (Ince et al., 2005), for sunflower stalk (Nazari et al., 2009) and for alfalfa stem. With increasing moisture content from 9.98% to 38.75% the mean value of the bending stress decreased from 43.25 to 23.99 MPa (by 1.8 times).

Table 1 Results of analyses of variance (Mean Square Error) for the tensile strength of safflower stalk

Source of variation	df	Mean Square Error	F value
Moisture content (M)	3	6832.508	219.611^{**}
Stalk region (R)	2	276.031	88.777^{**}
M × R	6	45.337	1.457^{ns}
Loading rate (L)	2	4988.736	160.348^{**}
M×L	6	291.386	9.366^{**}
R×L	4	106.983	3.439^{*}
M × R×L	12	70.654	2.271^{*}
Error	396	31.112	

Note: **-Significant at 1% level; * - Significant at 5% level; ^{ns} - not significant.

Table 2 Duncan's multiple range tests of the tensile strength values for the main factors

Items	Independent variable	Dependent variable (Tensile strength (MPa))
Moisture content /%	9.98	43.25 a
	17.85	32.25 b
	26.37	30.14 b
	38.75	23.99 c
Stalk region	Bottom	36.63 a
	Middle	33.38 b
	Top	27.96 c
Loading rate /mm min^{-1}	5	26.68 c
	10	32.86 b
	20	38.44 a

Note: The columns not followed by the same letter are significantly different at the 5% level of significant as judged by Duncan tests.

From the Table 2, according to Duncan's multiple range test results, it can be seen that for the tensile strength, the effect of moisture content at the levels of 9.98% and 17.85%, 9.98% and 26.37%, 9.98% and 38.75%, 17.85% and 38.75%, and 26.37% and 38.755 is significant at 5% level, while there is no significant difference between the effect of moisture contents of 17.85% and 26.37%.

The tensile strength also decreased towards the top regions of stalk (Table 2). This can be explained that the bottom region of safflower stalk is the oldest part of the plant and has the highest lignin content. Lignification causes the cell walls to thicken greatly, increasing their rigidity. Although the lignin content of the different regions was not recorded, it is probable that the increased magnitude of tensile strength towards the lower regions was due to increase in the lignin content (Nazari et al., 2009). The effect of height regions, on tensile strength, was also reported by Nazari et al. (2009) for alfalfa stems. The average values for the tensile strength were found to be 36.63, 33.38, and 27.96 MPa for the bottom, middle, and top regions respectively (Table 2). In the addition, according to Duncan's multiple range test results, the tensile strength mean values at different regions are statistically different from each other (P<0.05).

Table 3 shows the means comparison of the interaction between moisture content and stalk region on the tensile strength. In this table, the greatest tensile strength was obtained as 46.79 MPa, occurred in the bottom region and at the moisture content of 9.98%, while the lowest tensile strength was found to be 19.27 MPa in the top region at a moisture content of 38.75%.

Table 3 Means comparison of the interaction between moisture content and stalk region on the tensile strength of the safflower stalk

Moisture content/%	Stalk region		
	Tensile strength/MPa		
	Bottom	Middle	Top
9.98	46.79 a	44.16 b	38.82 c
17.85	37.03 c	32.05 d	27.69 e
26.37	36.16 c	31.19 d	26.09 e
38.75	26.56 e	26.16 e	19.27 f

Note: a-f: Mean values with common index are not significantly different (P>0.05) according to Duncan's multiple ranges test.

Figure 3 presents the relationship between the tensile strength and moisture content for all the stalk regions. As follows from the relations in the figure, for all the stalk regions considered, the tensile strength of stalks decreases with increase in their moisture content. Regression analysis was used to find and fit the best general models to the experimental data. Results showed that the tensile strength decreased as polynomial with the increasing moisture content in all regions. The relationship between the stalk tensile strength (σ_t, MPa), and moisture contents (M, %), for each stalk region, can be expressed by the following best-fit regression equations:

$$\sigma_t = 0.017M^2 - 1.457M + 50.74 \qquad R^2 = 0.988$$

for: Top region (2)

$$\sigma_t = 0.018M^2 - 1.546M + 56.61 \qquad R^2=0.990$$

for: Middle region (3)

$$\sigma_t = 0.005M^2 - 0.924M + 54.43 \qquad R^2 = 0.989$$

for: Bottom region (4)

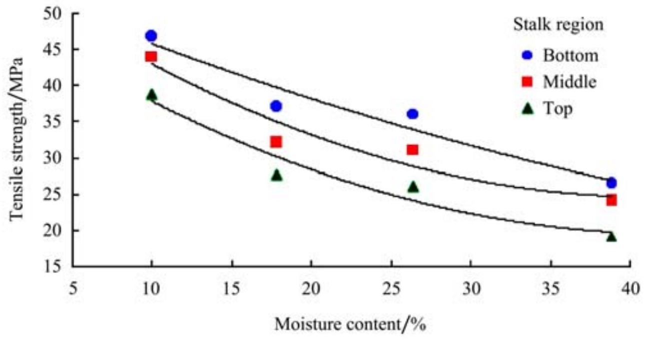


Figure 3 Changes of tensile strength with moisture content according to the stalk regions

The tensile strength increased with increasing in the loading rate (Table 2). This effect of loading rate, on tensile strength, was also reported by Nazari et al. (2009) for alfalfa stems. The mean values of tensile strength varied from 26.68 to 38.44 MPa when the rate of loading changed from 5 to 20 mm min^{-1} (Table 2). According to the Duncan's multiple range test results, the values of tensile strength were different from each other for the distinct rates of loading (Table 2).

The values of the interaction between loading rate and stalk region on the tensile strength are in Table 4. The values of this table varied from 23.31 to 43.94 MPa (Table 4). The minimum tensile strength (23.31 MPa) obtained for the top region with the lowest loading rate (5 mm min^{-1}), and the maximum tensile strength (43.94 MPa) obtained for the bottom region with the highest loading rate (20 mm min^{-1}). The tensile strength was greater in the bottom regions because of the accumulation of more mature fibers in the stem. Table 4 shows that the values of tensile strength increased from 28.98 to 43.98 MPa and from 23.31 to 32.45 MPa in the bottom and top regions respectively, as the loading rate increased from 5 to 20 mm mm^{-1}.

Table 4 Means comparison of the interaction between loading rate and stalk region on the tensile strength of the safflower stalk

Loading rate /mm min^{-1}	Stalk region — Tensile strength/MPa		
	Bottom	Middle	Top
5	28.98 d	27.78 d	23.31 e
10	37.02 b	33.42 c	28.14 d
20	43.94 a	38.96 b	32.45 c

Note: a-d: Mean values with common index are not significantly different (P>0.05) according to Duncan's multiple ranges test.

Figure 4 shows the variation of tensile strength with the loading rate for all the stalk regions. The models fitted to the data using the regression techniques, showed that the tensile strength increased linearly with increase in the loading rate for all the regions. Similar results were also reported by Nazari et al. (2009) for alfalfa stems. The following best-fit regression equations were found for the relationship between tensile strength (σ_t, MPa) and loading rate (V, mm min^{-1}) for each stalk region:

$$\sigma_t = 0.583V + 21.15 \quad R^2 = 0.954 \quad \text{for: Top region} \tag{5}$$

$$\sigma_t = 0.718V + 25.00 \quad R^2 = 0.969 \quad \text{for: Middle region} \tag{6}$$

$$\sigma_t = 0.955V + 25.48 \quad R^2 = 0.958 \quad \text{for: Bottom region} \tag{7}$$

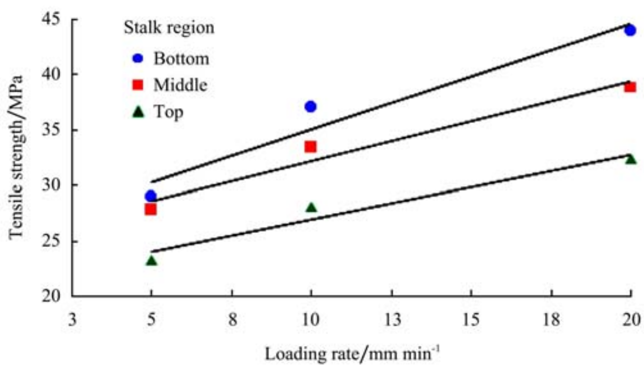


Figure 4 The changes of tensile strength with moisture content according to the stalk regions

4 Conclusions

From the results of this study, the following conclusions can be drawn:

1) The average tensile strength of safflower stalks, under different test conditions, was obtained as 32.38 MPa varying from 11.63 to 87.84 Mpa.

2) An increase in the moisture content of the safflower stalk led to a decrease in the tensile strength. The average values of the tensile strength varied from

43.25 to 23.99 MPa, as the moisture content increased from 9.98% to 38.75% (w.b).

3) The tensile strength decreased towards the top regions of stalk. The average values for the tensile strength were found to be 36.63, 33.38, and 27.96 MPa for the bottom, middle, and top regions respectively.

4) The tensile strength increased linearly with increases in the loading rate for all the regions. The values of tensile strength increased from 28.98 to 43.98 MPa and from 23.31 to 32.45 MPa in the bottom and top regions respectively, as the loading rate increased from 5 to 20 mm mm^{-1}.

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