

Effects of moisture content, internode region, and oblique angle on the mechanical properties of sainfoin stem

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Received: 07.02.2018 • Accepted/Published Online: 06.03.2019 • Final Version: 01.04.2019

Abstract: The effects of moisture content, internode region, and oblique angle on several mechanical properties of sainfoin stem were determined. The selected mechanical properties used were the shearing stress, specific shearing energy, bending stress, and modulus of elasticity when bending. The experiments were carried out with wet basis (WB) moisture contents of 71.76%, 45.57%, and 25.57%, at the third and second internode regions from the bottom up to the top, and 2 oblique angles (0° and 28°). The research results showed that the shearing stress of sainfoin stem increased as the moisture content increased, but decreased towards the upper internode of the stem. With the same moisture content, the shearing stress values obtained at an oblique angle of 28° were lower than those at an oblique angle of 0°. The maximum shearing stress and specific shearing energy were 5.76 MPa and 16.65 mJ mm⁻² with a WB moisture content of 71.76% and an oblique angle of 0° at the first internode, respectively. The bending stress increased with decreasing moisture content. The maximum bending stress was 36.45 MPa for the lower region with a WB moisture content of 25.57% and the modulus of elasticity when bending decreased with an increase in the moisture content, and it was towards the upper region. The average modulus of elasticity values varied between 1.60 and 0.64 GPa.

Key words: Sainfoin, shearing stress, specific shearing energy, bending stress, modulus of elasticity

1. Introduction

Field crops are defined as any of the herbaceous plants grown on a large scale in cultivated fields, primarily grains, forage, sugar, oil, or fiber crops that are used as raw material by various branches of industry (Zia-Ul-Haq et al., 2014; Ahmad et al., 2015; Cesur et al., 2018).

Sainfoin (*Onobrychis viciifolia*) is a perennial, deep-rooted, drought-resistant, common forage legume. It is a good source for animal feeding, veterinary, soil improvement, and bee pollen and nectar. It ranks third among forage legumes after alfalfa and cow vetches, with acreage of 193,694 ha, and had a production of 1,982,047 tons in Turkey in 2016 (TÜİK, 2017). Information about the physical and mechanical properties of the plants is necessary in the design and development of machines such as choppers, mowers, harrows, and balers. Methods and procedures for determining the mechanical and rheological properties of agricultural products were described by Mohsenin (1980). Several studies have been conducted to determine the mechanical properties of plants. The bending and shearing properties of the stem or stalk of plants, together with the modulus elasticity

when bending, are important mechanical properties for the design of cutting or chopping units. These mechanical properties vary depending on the species, variety, climatic conditions, stalk diameter, plant stem height, moisture content, cellular structure, and maturity. Many studies have been carried out to determine the mechanical properties of plant stems, such as sorghum (Cattopadhyay and Pandey, 1999), hemp (Chen et al., 2004), sunflower (İnce et al., 2005), alfalfa (Nazari Galedar et al., 2008), safflower (Özbek et al., 2009), wheat (Eseghbeygi et al., 2009; Tavakoli et al., 2009), canola (Hoseinzadeh and Shirmeshan, 2012), *Miscanthus* (Liu et al., 2012), and selected biomass (Yu et al., 2014). These studies showed that the mechanical properties of plant stems were related to the region of the plant stem, stem diameter, stem thickness, moisture content, and type and cutting angle of the knife used. Leblicq et al. (2015) mechanically analyzed the bending behavior of plant stems and reported that the bending process of the plants was significantly affected by the crop species, growing conditions, and diameter and wall thickness of the stem. Chen et al. (2004) reported that on average, the cutting energy for hemp stem with a

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high wet basis (WB) moisture content of 51% was higher than those with low moisture content. Cattopadhyay and Pandey (1999) found that the specific cutting energy increased from 34.1 to 101.1 mJ mm^{-2} during the forage stage with an increase in the knife bevel angle from 30° to 70° . İnce et al. (2005) determined that the modulus elasticity of sunflower stem was 1251.28, 1503.61, 2019.00, and 2210.89 MPa with WB moisture contents of 75%, 55%, 30%, and 15%, respectively. Moreover, they reported that the bending stress with low WB moisture content was approximately 80% higher than with high moisture content. Similarly, Özbek et al. (2009) found that the bending stress of safflower stem varied from 54.02 to 13.81 MPa with a WB moisture content of 11.13% to 41.67%, respectively. Nazari Galedar et al. (2008) stated that the shearing strength and shearing energy values of alfalfa stem with the highest moisture content were approximately 2 and 3 times greater than those with the lowest moisture content. Tavakoli et al. (2009) found that the shearing stress values of wheat stem were within the ranges of 6.81–10.78, 7.02–11.49, and 7.12–11.78 MPa at the first, second, and third internodes from top to bottom, respectively. Hoseinzadeh and Shirmeshan (2012) reported that the effect of variety on the shearing strength, bending stress, and Young's modulus of canola stem was significant. They found that the shearing strength, maximum bending stress value, and Young's modulus were 1.32 MPa, 48.1 MPa, and 2040 GPa for the Opera variety stems. One of the most important parts of a harvesting machine is the knife. The cutting force and energy are affected by plant factors, the knife blade design, and operation mode and knife angles (Ghahraei et al., 2011). Kolor (2007) found that the lowest specific cutting energy values for paddy stem were provided with a bevel angle and oblique angle of 28° and 30° , respectively. Liu et al. (2012) reported that a serrated blade required less cutting force and cutting energy than those of a flat blade for cutting *Miscanthus* stem. They obtained maximum cutting force values of 83.0 and 54.6 N mm^{-1} and specific cutting energy of 87.5 and 66.1 mJ mm^{-2} with a flat blade and a serrated blade, respectively. Esehaghbeygi et al. (2009) compared the effect of the 3 oblique angles (0° , 15° , and 30°) on shearing stress. They found that the lowest shearing stress value was obtained at an oblique angle of 30° .

The mechanical properties for many plant varieties have been determined by researchers. However, no research exists involving the mechanical properties of sainfoin stem. The main objective of this study was to determine the shearing stress, specific shearing energy, bending stress, and modulus elasticity of sainfoin stem. Thus, an important gap will be closed.

2. Materials and methods

2.1. Theoretical background

2.1.1. Shearing

The shearing properties of a stem are the maximum shearing stress and specific shearing energy. The maximum shearing stress was calculated by the following equation (Mohsenin, 1980; Chattopadhyay and Pandey, 1999; İnce et al., 2005):

$$\tau = \frac{F_s}{A} \quad (1)$$

where τ is the maximum shearing stress in MPa, F_s is the maximum shearing force in N, and A is the cross-sectional wall area of the stem at the plane of shear in mm^2 . The shearing energy was found by determining the area under the force-displacement curve with the aid of Riemann sum approximation through Microsoft Excel. The specific shearing energy was calculated by dividing the shearing energy by the cross-sectional wall area (A) of the stem:

$$E_{ss} = \frac{E_s}{A} \quad (2)$$

where E_{ss} is the specific shearing energy in mJ mm^{-2} and E_s is the shearing energy in mJ.

2.1.2. Bending

The bending properties of a stem are failure bending stress, specific bending energy, and modulus of elasticity. The failure bending stress of the stem was calculated by the following equation (Chattopadhyay and Pandey, 1999; Srivastava et al., 2006):

$$\sigma = \frac{F_u Lc}{I} \quad (3)$$

where σ is the bending stress at failure in MPa, F_u is the ultimate bending force at which the stem fails in N, L is the distance from the point of tying to the point of support in mm ($L = 40$ mm), c is the distance between the neutral axis and outmost fiber of the stem in mm, and I is the moment of inertia of the cross-section about its neutral axis in mm^4 .

The modulus of elasticity when bending for a cantilever beam is expressed by the following equation (Srivastava et al., 2006):

$$E = \frac{F_b L^3}{3DI} \quad (4)$$

where E is the modulus of elasticity in MPa, F_b is bending force corresponding to the deflection at the midpoint of the linear part of the bending force-deflection curve in N, D is the deflection at the midpoint of the linear part of the bending force-deflection curve in mm ($D \approx 4.0$ mm) (ASABE, 2012a), and 3 is the constant for the cantilever beam. On the other hand, the product EI is defined as the bending stiffness of the beam.

2.2. Sample preparing

Sainfoin (cultivar Lütüfubey) samples were collected from the production fields of the East Anatolian Agricultural Research Institute in Erzurum, Turkey. The plants were manually cut during the blooming stage. The fresh-cut plants were divided into 3 groups, where one group was tested immediately, and the other 2 groups were left to naturally dry with various moisture contents. The fresh-cut samples had a WB moisture content of 71.76%, and the other 2 WB contents were 45.57% and 25.57%. The moisture contents of the stem samples were determined using the oven drying method (ASABE, 2012b). The mean diameter of the sainfoin stem at the first, second, and third internode was 5.45 ± 0.55 , 4.94 ± 0.43 , and 4.32 ± 0.51 mm, respectively. The mean wall thickness of the sainfoin stem at the first, second, and third internode was 1.25 ± 0.25 , 1.05 ± 0.20 , and 1.01 ± 0.18 mm, respectively.

2.3. Shearing test

In order to measure the shearing stress, a quasistatic loading device was developed (Figure 1). An apparatus was mounted on the upper head of the device to hold the stem material over the counter shear to be cut by a knife. The stem samples were sheared by a commercial single-sickle knife section at a bevel angle of 30° and oblique angle of 28° , which has been used in mowers. The thickness of the sickle knife was 3 mm, and the knife-edge was serrated. The clearance between the knife section and counter shear was selected as 0.5 mm to prevent friction. The shearing force was applied with a constant knife speed of 52 mm min^{-1} on the stem until reaching the displacement value at which the stem failed. The selected knife speed was in accordance with the literature for laboratory tests. Persson (1987) determined that cutting power was only slightly

affected by cutting speed, between 1.72 and 5.2 m s^{-1} . Koc and Liu (2018) stated that the cutting force of switchgrass remained stable as the cutting speed increased from 3 to 370 mm s^{-1} . Several researchers determined the shearing stress of plant stems with a constant knife speed such as 200 mm min^{-1} (Esehaghbeygi et al., 2009), 100 mm min^{-1} (Baran et al., 2015), 25.4 mm min^{-1} (Igathinathane et al., 2010), 10 mm min^{-1} (Nazari Galedar et al., 2008), 1.2 mm s^{-1} (İnce et al., 2005), and 0.4 mm s^{-1} (Özbek et al., 2009). During the shearing process, the shearing force applied on the stem was sensed against time by a load cell with a capacity of 200 N and the data were transmitted to the computer with the aid of a data acquisition system (DAQ), and then recorded. The sampling rate was 20 force values per second. The shearing force-time curves were converted to shearing force-displacement curves by multiplying the time values by the constant knife speed. The typical force-displacement curve for sainfoin stem is shown in Figure 2. From the force-displacement data, the maximum shearing stress and specific shearing energy were calculated using Eqs. (1) and (2).

2.4. Bending test

The plant was subjected to the bending force until reaching the deflection value at which the stem failed. The measurement system used to acquire the bending properties of sainfoin consisted of 3 main components: a driving unit for horizontal pulling movement, an apparatus in which the plant stem was placed, and the DAQ for measuring the bending force (Figure 3). The stem sample was connected to a load cell with a capacity of 200 N, which was tied at a certain height using an inelastic rope, and then bent by pulling the rope horizontally at a constant speed of 60 mm min^{-1} until it failed. The distance from the bottom to the

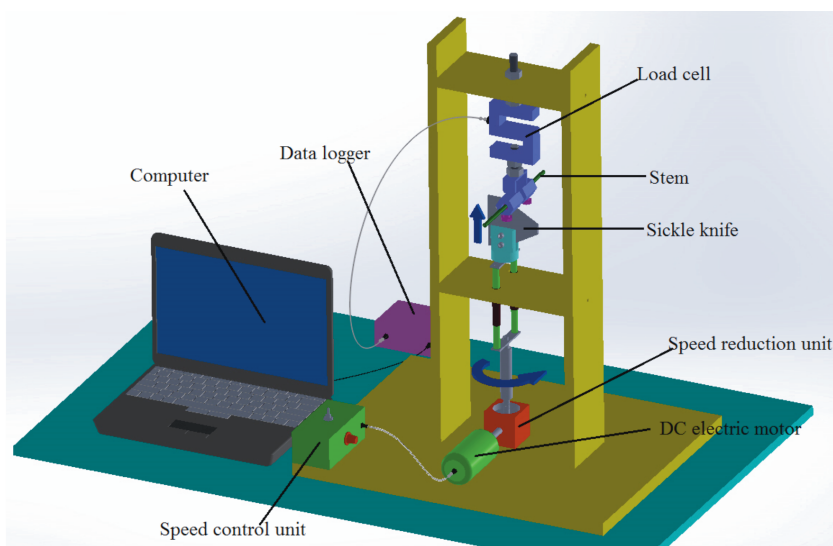


Figure 1. Apparatus used to measure the shearing stress of the sainfoin stem.

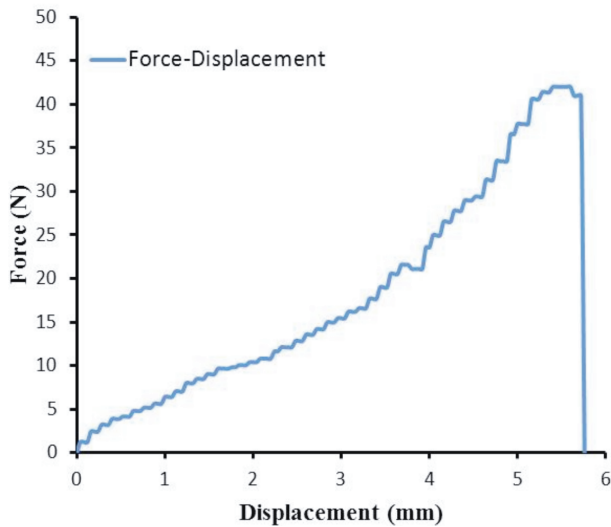


Figure 2. Typical shearing force-displacement curve for the sainfoin stem.

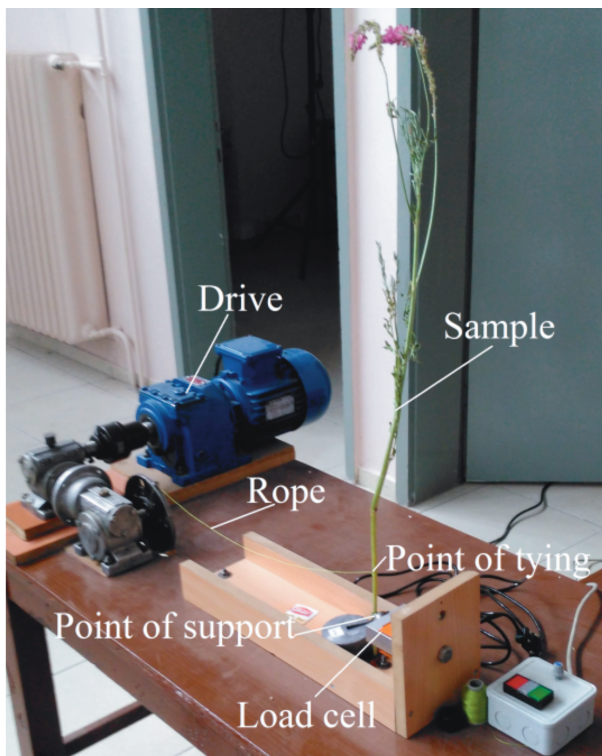


Figure 3. System used to measure the bending of the sainfoin stem.

support point was 75 mm and from the point of support to the point of tying was 40 mm. The bending force applied on the stem was measured with a load cell and recorded with respect to time by means of the DAQ, similar to that

explained in the above subsection. Since the loading rate was fixed, the force-deflection curves were obtained from the data of the force-time by multiplying the time by the velocity. The typical force-deflection curve for the stems of sainfoin is shown in Figure 4. From the force-deflection data, the modulus of elasticity, stem failure stress, and bending energy were calculated using Eqs. (3) and (4).

Based on the preliminary experiments, 5 replicates were used for the shearing and bending tests, respectively, to reduce the standard deviations among the measurements.

2.5. Experimental design

In order to acquire the shearing properties of sainfoin stem, such as the maximum shearing stress and specific shearing energy, the independent variables were selected as 3 WB moisture content levels (71.76%, 45.57%, and 25.57%), 2 oblique angles (0° and 28°) (Figure 5), and 3 stem regions (first, second, and third internodes) (Figure 6).

For determining the bending properties of the stems, such as failure bending stress and modulus of elasticity, the independent variables were 3 WB moisture content levels (71.76%, 45.57%, and 25.57%) and 2 stem regions (first and second internodes).

3. Results and discussion

3.1. Effect of moisture content, internode, and oblique angle on the shearing stress

The shearing stress values of sainfoin stem varied depending on the internode region, moisture content, and oblique angle of the knife. The results obtained from the shearing test are shown in Figure 7. This figure shows an

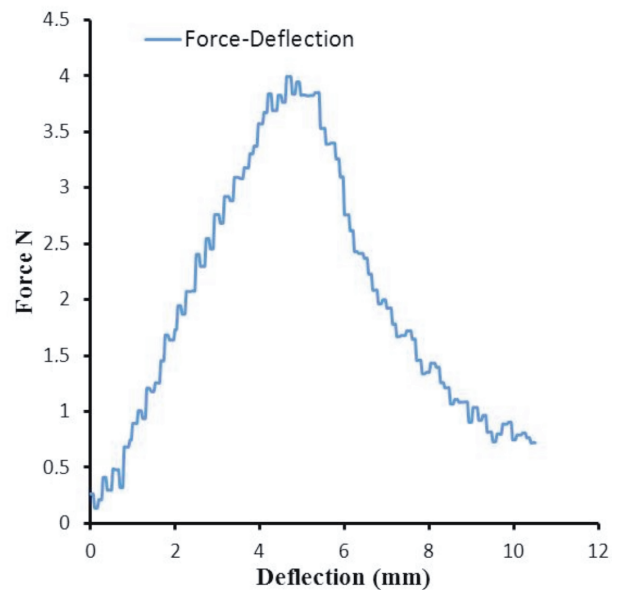


Figure 4. Typical bending force-deflection curve for the sainfoin stem.

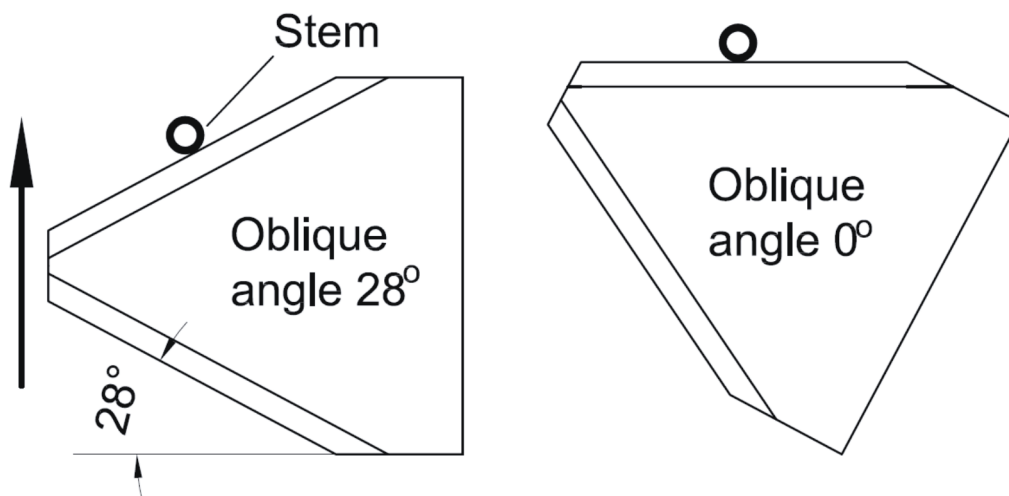


Figure 5. Knife mounted at different oblique angles representing 28° oblique angle (left) and 0° oblique angle (right).



Figure 6. Regions identifying the internodes of the sainfoin stem in the shearing and bending tests.

increasing relationship between the shearing stress and moisture content at all of the internodes. The shearing stress increased as the moisture content increased at all of the internodes. Similarly, this trend was obtained for the stems of sunflower (İnce et al., 2005), alfalfa (Nazari

Galedar et al., 2008), wheat (Eseghbeygi et al., 2009; Tavakoli, et al., 2009), and safflower (Özbek et al., 2009). Kushaha et al. (1983) stated that the shearing stress values of wheat straw varied from 7 to 22 MPa for WB moisture contents ranging from 5% to 30%. Similarly, in a study to determine the mechanical properties of wheat, Esehaghbeygi et al. (2009) determined that the average shearing stresses were 3.25, 3.57, 3.69, and 3.86 MPa for WB moisture contents of 15%, 25%, 35%, and 45%, respectively. The maximum shearing stress values were obtained with an oblique angle of 0° at all of the internodes with the same moisture content. The highest shearing stress value was 5.76 MPa with a WB moisture content of 71.76% and oblique angle of 0° at the first internode. The lowest shearing stress value was 1.64 MPa with a WB moisture content of 25.57% and oblique angle of 28° at the third internode. The shearing stress decreased towards the upper internode of the stem. Similar results, that the shearing stress decreased as the cutting height increased, were reported for sunflower (İnce et al., 2005), safflower (Özbek et al., 2009), wheat (Tavakoli, et al., 2009), and selected biomass (Yu et al., 2014). Esehaghbeygi et al. (2009) and Kolor (2007) showed that an oblique angle of 30° was sufficient to reduce the shearing stress of paddy and wheat stems. With this research, it was found that an oblique angle of 30° was sufficient to reduce the shearing stress of sainfoin stem.

3.2. Effect of moisture content, stem region, and oblique angle on the specific shearing energy

The different sainfoin stem moisture contents, internode regions, and oblique angles led to a change in the specific shearing energy. There was a significant difference between the highest and lowest values in terms of the specific

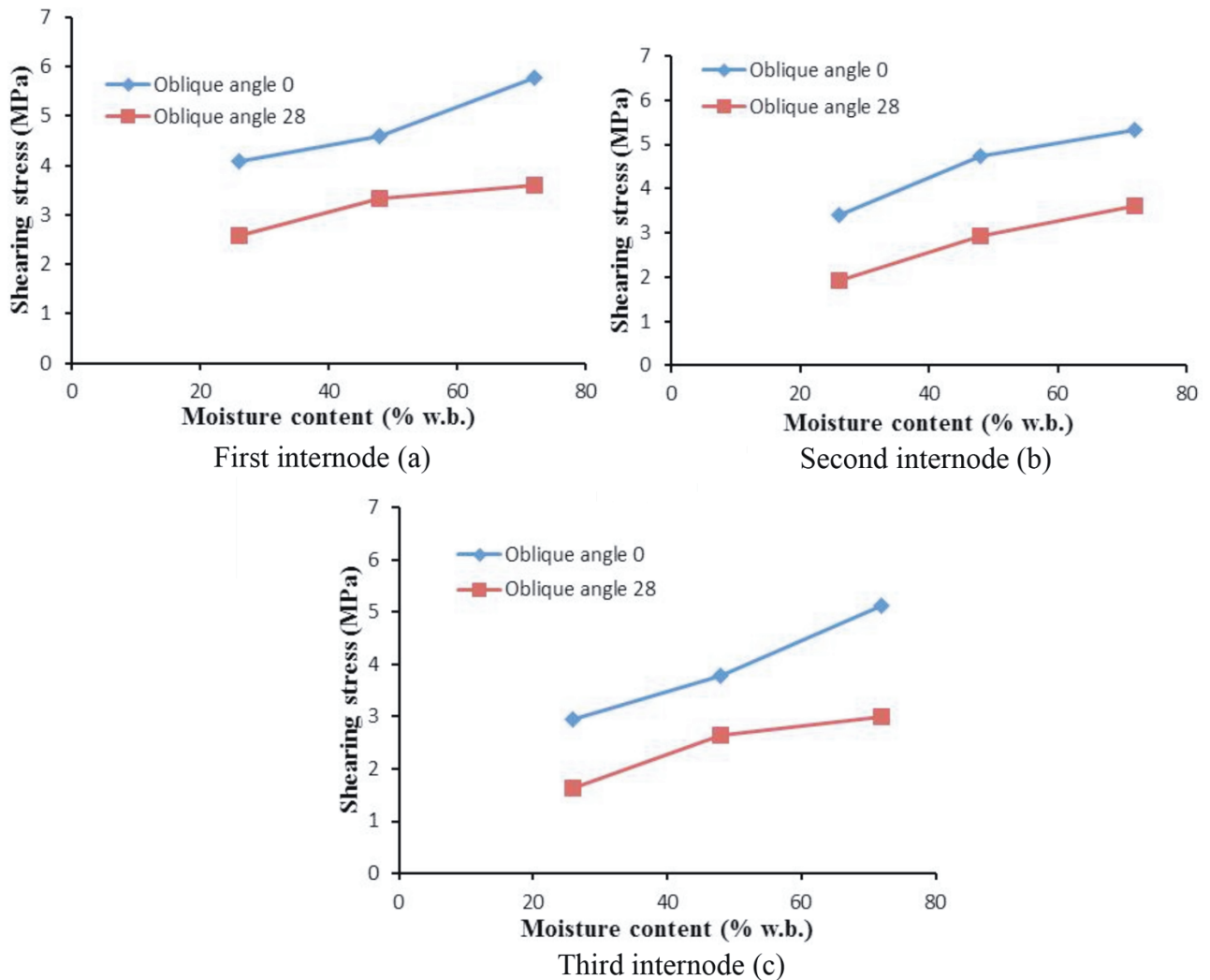


Figure 7. Effect of the moisture content and oblique angle on the shearing stress: first internode (a), second internode (b), and third internode (c).

shearing energy. The results of the specific shearing energy obtained from each sainfoin stem internode with different moisture contents and oblique angles of 0° and 28° are given in Figure 8. The specific shearing energy of sainfoin stem increased while the moisture content increased, as reported in previous studies for sunflower stem (İnce et al., 2005), safflower (Özbek et al., 2009), and wheat (Tavakoli, et al., 2009). The shearing energy requirement increased with an oblique angle of 0° at all of the internodes. The highest specific shearing energy was obtained as 16.65 mJ mm⁻² with a WB moisture content of 71.76% and oblique angle of 0° at the first internode. The lowest specific shearing energy was obtained as 4.09 mJ mm⁻² with a WB moisture content of 25.57% and oblique angle of 28° at the third internode. The specific shearing energy decreased from the lower up to upper internodes. The values varied from 7.71 to 10.66 mJ mm⁻², 5.61

to 9.89 mJ mm⁻², and 4.09 to 7.07 mJ mm⁻² at the first, second, and third internodes with an oblique angle of 28°, respectively, for the different moisture contents studied. Similar results were obtained with sunflower (İnce et al., 2005), safflower (Özbek et al., 2009), wheat (Tavakoli et al., 2009), and selected biomass (Yu et al., 2014). The value of the specific shearing energy at the first internode was higher because of the accumulation of more mature fibers in the stem. There was a difference between oblique angles of 0° and 28° in terms of the specific shearing energy, where an oblique angle of 28° led to reduced specific shearing energy. Mathanker et al. (2015) investigated the cutting energy required for energy cane stems using 3 oblique angles (0°, 30°, and 60°). They found that the highest cutting energy was obtained with an oblique angle of 0°, while the lowest cutting energy was obtained from oblique angles of 30° and 60°.

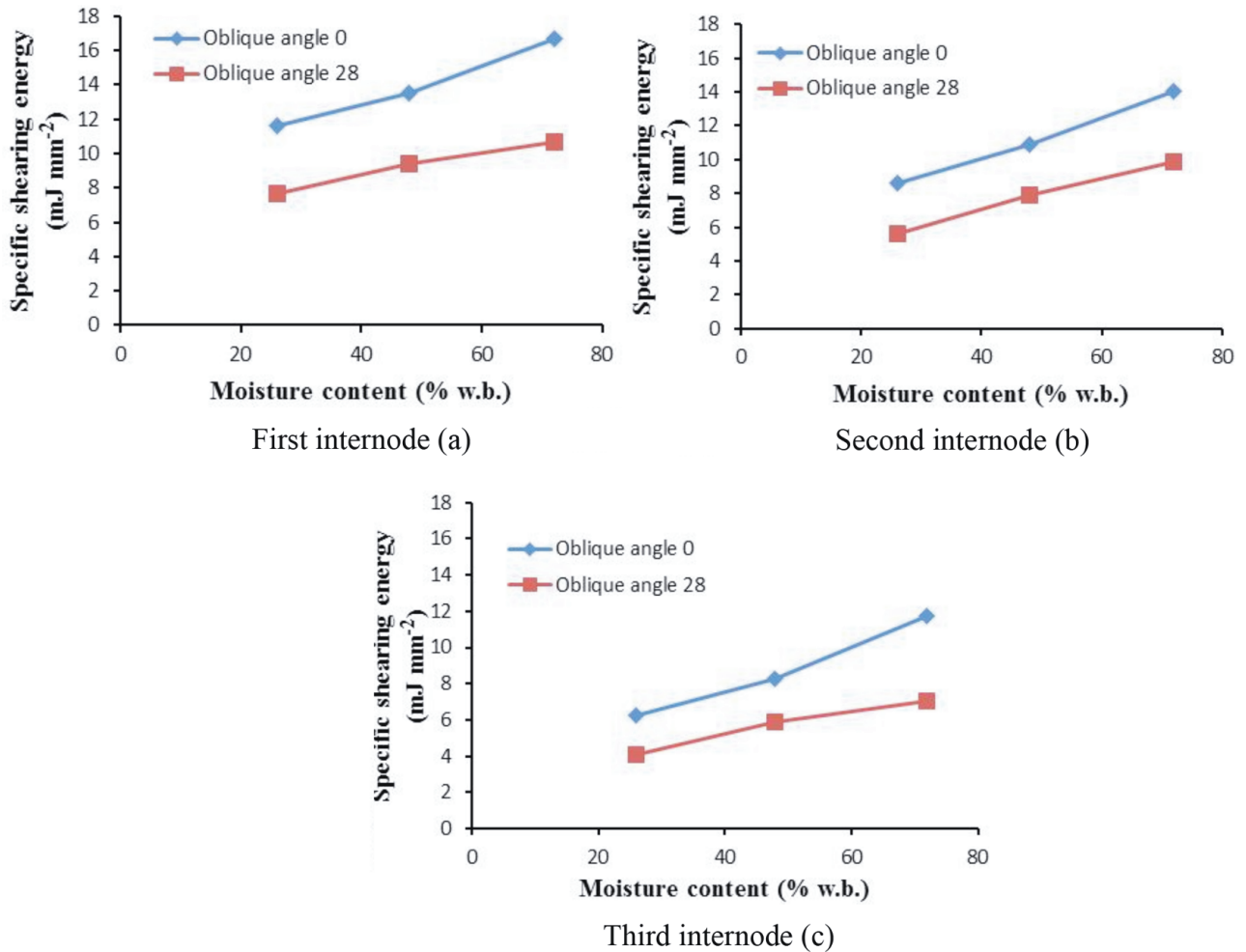


Figure 8. Effect of the moisture content and oblique angle on a specific shearing energy: first internode (a), second internode (b), and third internode (c).

3.3. Effect of moisture content and internode region on the bending stress

The bending stress was assessed as a function of the moisture content and stem regions. The bending stress of the stem regions decreased with an increase in moisture content (Figure 9). Hence, an increase in the moisture content caused a reduction in the brittleness of the sainfoin stem. The same trend was reported by other researchers for sunflower (İnce et al., 2005), alfalfa (Nazari Galedar et al., 2008), safflower (Özbek et al., 2009), wheat (Esehaghbeygi et al., 2009; Tavakoli, et al., 2009), and canola (Hoseinzadeh and Shirmeshan, 2012).

With the same moisture content, the bending stress at the lower internode region was higher than those at the upper internode regions. Therefore, it was observed that the upper internode region was more flexible in comparison with the lower internode region. Similarly, Chandio et al. (2013) determined that the bending

stress was highest at the lower internode region, while it was the lowest at the upper internode region for wheat and rice straw. They found that the bending stress decreased towards the upper internode region in both plants. Likewise, Esehaghbeygi et al. (2009) found that the bending stress of wheat stem was 21.14, 20.21, and 17.85 MPa at internode regions of 100, 200, and 300 mm, respectively. The bending stress increased towards the upper internode region, contrary to the result of Tavakoli et al. (2009) for wheat straw. The maximum bending stress was 36.45 MPa for the lower internode region with a WB moisture content of 25.57%. The minimum bending stress value was 18.50 MPa for the upper region with a WB moisture content of 71.76%. The bending stress for the lower and upper internode regions was 18.50, 26.05, and 36.45 and 13.85, 20.02, and 26.60 MPa with WB moisture contents of 71.76%, 45.57%, and 25.57%, respectively.

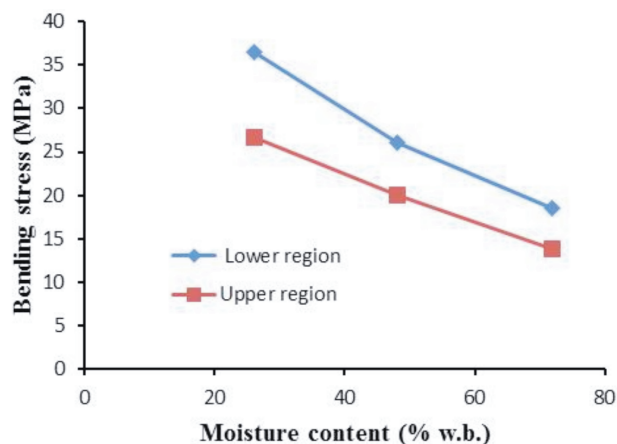


Figure 9. Effect of the moisture content and internode region on the bending stress.

3.4. Effect of moisture content and stem region on the modulus of elasticity

The modulus of elasticity changed as a function of the moisture content and height of the sainfoin stem. Hoseinzadeh and Shirmeshan (2012) determined that the modulus of elasticity of canola stem varied significantly according to the variety, moisture content, and amount of fertilizer applied. As shown in Figure 10, the modulus of elasticity during bending decreased with increased moisture content at the lower and upper internode regions of the stem. A similar trend was reported for sunflower (İnce et al., 2005), alfalfa (Nazari Galedar et al., 2008), safflower (Özbek et al., 2009), wheat (Esehaghbeygi et al., 2009; Tavakoli, et al., 2009), and canola (Hoseinzadeh and Shirmeshan, 2012). Galedar et al. (2008) reported that the modulus of elasticity of alfalfa stem was 0.79, 1.80, 3.52, and 3.99 GPa with WB moisture contents of 80%, 40%, 20%, and 10%, respectively. The modulus of elasticity of the sainfoin stem decreased towards the upper internode of the stem. The modulus of elasticity during bending decreased from the base up to the top, as was reported for wheat straw by Esehaghbeygi et al. (2009). Similarly, Kaack and Schwarz (2001) found that the modulus of elasticity of *Miscanthus* and flexural rigidity decreased significantly and linearly from the lower to the upper part of the stems. A high modulus of elasticity prevents the plant from bending as a result of wind and gravity, and keeps the stems upright. The average modulus of elasticity during bending was 0.91, 1.14, and 1.60 GPa and 0.64, 1.03, and 1.26 GPa with WB moisture contents of 71.76%, 45.57%, and 25.57% at the lower and upper internode regions, respectively.

3.5. Conclusions

Investigations of the mechanical properties and behavior of crops are important for the design and development of

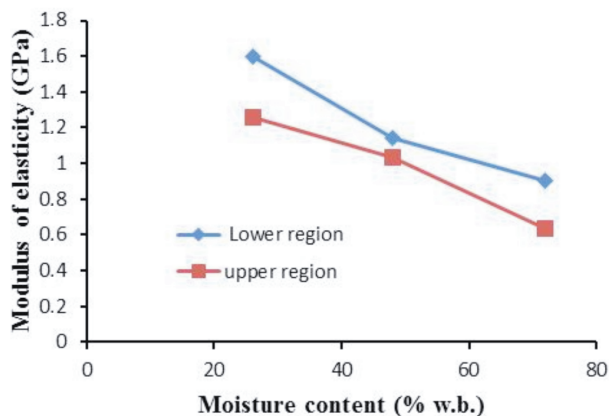


Figure 10. Effect of the moisture content and internode region on the modulus of elasticity.

the harvest, threshing, and processing machinery. This study was conducted to determine the shearing stress, specific shearing energy, bending stress, and modulus of elasticity when bending sainfoin stem. Experimental tests were carried out with WB moisture contents of 71.76%, 45.57%, and 25.57%, at the third and second internode regions from the bottom up to the top, and 2 oblique angles (0° and 28°). The results showed that the mechanical properties depended on the moisture contents and internode regions of the sainfoin stem. The following results were concluded from the results of this study.

The shearing stress and specific shearing energy decreased from the first to the third internode region. A decrease in the moisture content of the sainfoin stem led to a decrease in the shearing stress and specific shearing energy. An oblique angle of 0° resulted in increased shearing stress and specific shearing energy when compared to those at an oblique angle of 28° . The highest shearing stress and specific shearing energy were obtained as 5.76 MPa and 16.65 mJ mm^{-2} with a WB moisture content of 71.76% and oblique angle of 0° at the first internode, respectively. Hence, it is recommended that sainfoin stem be cut and harvested at lower moisture contents to reduce the shearing stress and specific shearing energy requirements.

Both the bending stress and modulus of elasticity decreased with an increase in moisture content and from the lower to the upper internode region. The bending stress of sainfoin stem at the lower and upper internode regions decreased from 36.45 to 26.60, 26.05 to 20.02, and 18.50 to 13.85 MPa with increased moisture content, respectively.

The modulus of elasticity of sainfoin stem for the lower and upper internode regions also decreased from 1.60 to 1.26, 1.14 to 1.03, and 0.91 to 0.64 GPa with increased moisture content, respectively.

This study, conducted to determine the mechanical properties of sainfoin stem, will be greatly helpful to designers of sainfoin equipment, harvesting machines, and tillage implements.

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Nomenclature			
τ	Maximum shearing stress, MPa	L	Distance from the point of tying to the point of support, mm
F_s	Maximum shearing force, N	c	Distance between the neutral axis and outmost fiber of the stem, mm
A	Cross-sectional wall area of the stem, mm ²	I	Moment of inertia of the cross section about its neutral axis, mm ⁴
E_{ss}	Specific shearing energy, mJ mm ⁻²	E	Modulus of elasticity, MPa
E_s	Shearing energy, mJ	F_b	Bending force corresponding to the deflection at the midpoint of linear part of the bending force, N
σ	Bending stress at failure, MPa	D	Deflection at the midpoint of the linear part of the bending force, mm
F_u	Ultimate bending force, N		