Int. Agrophysics, 2009, 23, 27-30

INTERNATIONAL
Agrophysics
www.international-agrophysics.org

Influence of moisture content, rate of loading and height regions on tensile strength of alfalfa stems

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Received February 1, 2008; accepted September 9, 2008

A b s t r a c t. The objective of this study was to determine tensile strength of alfalfa stems as a function of moisture content, rate of loading and height region. Information on the physical and mechanical properties of alfalfa stem is important for the design of machines such as mowers, balers and choppers. The experiments were conducted at four moisture levels of 10, 20, 40, and 80% w.b., and three rates of loading of 5, 10 and 20 mm min^{-1}. Each alfalfa stem was divided equally into three height regions, as upper, middle and lower. The tensile strength increased exponentially with decrease in the moisture content and towards the lower regions. The values of the tensile strength were within 9.24-26.35, 16.31-32.74, and 28.88-43.82MPa for the upper, middle and lower regions, respectively, at the different moisture contents studied and 10 mm min^{-1} rate of loading. The tensile strength increased linearly with increases in the rate of loading for all the regions. Its values varied between 9.24-12.27, 16.31-20.46, and 28.80-32.75 MPa for the upper, middle and lower regions, respectively, with increases in the rate of loading from 5 to 20 mm min^{-1}, at the moisture content of 80% w.b.

K e y w o r d s: alfalfa, stem, tensile strength, height region, rate of loading

INTRODUCTION

Alfalfa (*Medicago sativa* L.), an excellent source of protein, vitamins and minerals, is the most important forage crop species in Iran. Information on the physical and mechanical properties of alfalfa stem is important for the design of machines such as mowers, balers and choppers. Most research in the area of mechanical and physical properties of agricultural products can be classified as:

– the application of fundamental principles of mechanics to the mechanical behaviour of biological materials, and
– the adaptation of test procedures, originally developed for non-biological products, to biological or agricultural materials (El Hag *et al*., 1971).

Most studies on the mechanical properties of plants have been carried out during their growth, using failure criteria (force, stress and energy) or their Young modulus and the modulus of rigidity. Studies have focused on plant anatomy, lodging processes, harvest optimisation, animal nutrition, industrial applications and the decomposition of wheat straw in soil (McNulty and Moshenin, 1979; Annoussamy *et al*., 2000). The physical properties of cellular material that are important in cutting are compression, tension, bending, density and friction. These properties depend on the species, variety, stalk diameter, maturity, moisture content and cellular structure (Bright and Kleis, 1964; Persson, 1987). These physical properties also vary along the plant stalk. It is also necessary to determine the physico-mechanical properties, such as the bending and shearing stress, and energy requirements for suitable knife designs to be developed and for operational parameters to be optimised (Ince *et al*., 2005). Hall *et al*. (1967) studied the viscoelastic properties of alfalfa stems and found that alfalfa stems behave as viscoelastic materials, rather than as viscoplastic materials. Methods and procedures for determining most of the mechanical and rheological properties of agricultural products have been described by Mohsenin (1986).

Ultimate tensile strength has been measured by some workers *eg* Prince (1961), Halyk and Splinter (1968). Halyk (1962) determined the tensile and shear strength of alfalfa stems and developed regression equations relating tensile strength to moisture and density. Halyk and Splinter (1968)

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found that alfalfa had a tensile strength in the range 9-36 MPa and that it was negatively linearly correlated with moisture content. O'Dogherty (1981), examining moisture contents in the range of 10-30% w.b., reported a range of tensile strengths of 9-32 MPa for wheat straw (var. Fenman). Ahlgrimm (1970) showed that for grass increasing moisture content reduced tensile strength but at a decreasing rate. The values ranged from 108 to 294 MPa, were based on a dry bearing area, the results being 5-10 times greater than if failure stresses were calculated based on the whole stem area. There are no studies on the influence of moisture and rate of loading on tensile strength of alfalfa stems.

The aim of this study was to measure the tensile strength of alfalfa stem and to determine the relationship between that and the moisture content, rate of loading and height regions of alfalfa stem.

MATERIALS AND METHODS

The test specimens were randomly selected from shoots that were cut from an experimental plot of alfalfa (cv. Hamedani) located on the University of Tehran agronomy farm. All plants were in the 1-10 stages of maturity and second cutting (Prince *et al*., 1969). Petioles and leaves at the nodes were removed prior to any treatment or measurement. Test specimens were selected according to such measurable physical parameters as moisture content and height region. The diameter of the alfalfa stem decreased towards the top of the plant. Therefore, it was divided equally into three height regions as upper, middle and lower. The freshly cut shoots were divided into four samples: one sample was used for immediate testing (fresh-cut), and the other samples were set aside for testing after they had dried naturally to various moisture contents. To determine the average moisture contents of the alfalfa stem on the date of the test, the specimens were weighed and dried at 103°C for 24 h (ASAE, 2006) in the oven and reweighed. Experiments were conducted at a moisture content of 10, 20, 40, and 80% w.b. The diameter of the specimen was measured by a micrometer (Mitutoyo, Japan). The average major diameter of the stems in the upper, middle and lower regions varied between 1.97-2.60, 3.49-3.72, and 3.41-4.04 mm, respectively. The average minor diameter of the stems in the upper, middle and lower regions varied between 1.61-2.25, 2.77-3.36, and 3.11-3.89 mm, respectively.

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 are similar to those reported in most of the literature concerned with such work *eg* O'Dogherty (1981), O'Dogherty *et al*. (1995). 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 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 (Fig. 1). 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 testing machine (Instron Universal Testing Machine/SMT-5, SANTAM Company, Tehran, Iran). Three rates of loading 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. A typical force-deformation curve is shown in Fig. 2. The tensile failure stress (or ultimate tensile strength), σ_t, of the specimen was calculated by:

$$\sigma_t = \frac{F_t}{A}, \quad (1)$$

where: F_t is the tension force at failure and A is the wall area of the specimen at the failure cross-section.

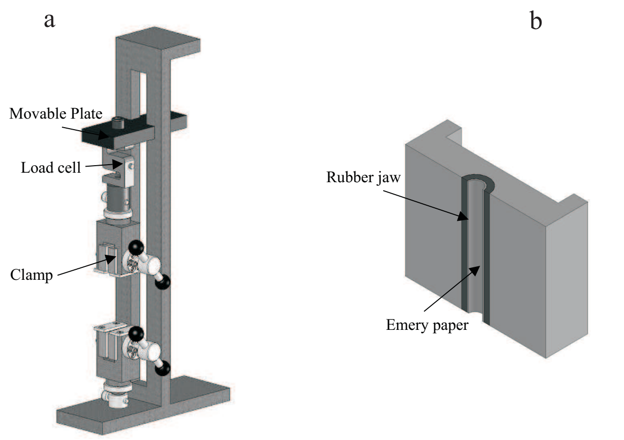

Fig. 1. Apparatus for the measurement of tensile strength: a – schematic of apparatus, b – clamp.

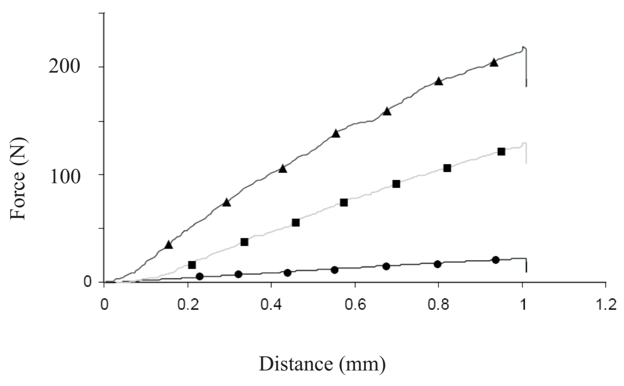

Fig. 2. Typical force-deformation plot which resulted from tension loading of a specimen: ▲ upper, ■ middle, and ● lower regions.

A completely randomised design involving factorial treatment combination was used. The independent variables were moisture content, rate of loading and height regions. The dependant variable was tensile strength. The experiments were conducted at four levels of moisture, of 10, 20, 40, and 80% w.b. and three levels rates of loading – of 5, 10, 20 mm min^{-1}. The level of height regions were upper region, middle region and lower region. The numbers of replications used were between 10 and 15 for each combination of the experimental parameter. The data were analysed statistically using SPSS software (vers. 13, SPSS, Inc., Chicago, IL, USA).

RESULTS AND DISCUSSION

The value of the tensile strength varied between 9.24 and 26.35 MPa, 16.31 and 32.74 MPa, and 28.88 and 43.82 MPa for the upper, middle and lower regions, at the different moisture contents studied and 10 mm min^{-1} rate of loading (Fig. 3a). The tensile strength increased exponentially with decrease in the moisture content and towards the lower regions (Fig. 3). This may be explained by increasing of the dry matter differences between the regions at low moisture contents. The lower region of alfalfa stem is the oldest part of the plant and has the highest lignin content. Lignification causes the cell walls to thicken greatly, increasing their rigidity (Shinners *et al*., 1987). 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. The effect of moisture content and height regions was also reported by O'Dogherty *et al*. (1995) for wheat straw, and by Halyk (1962) for alfalfa stems. Halyk (1962) reported that a range of 9-36 MPa was found, with a negative linear correlation with moisture content. In addition, using Duncan's multiple range tests, the values for the shearing stress at the lower region were found to differ from those for the middle and upper levels. The equations representing relationship between tensile strength and moisture content for each height region and their coefficient of determination (R^2) are presented in Table 1.

The tensile strength increased linearly with increase in the rate of loading for all the regions (Fig. 3b). This effect of rate of loading was also reported by El Hag *et al*. (1971) for cotton stalk. The values of tensile strength varied from 9.24 to 32.79 MPa in the upper region under the lowest rate of loading, and the lower region under the highest rate of loading, respectively. The tensile strength also decreased towards the upper regions. Its values varied between 9.24-12.27, 16.31-20.46, and 28.80-32.75 MPa for the upper,

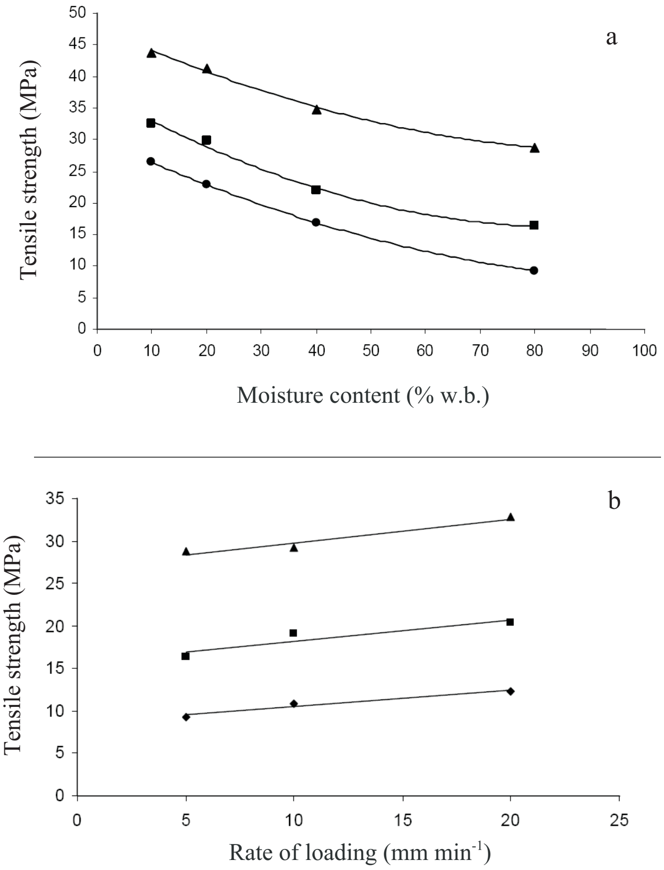

Fig. 3. Changes of tensile strength with: a – moisture content, b – rate of loading according to the regions: ▲ lower; ■ middle, and ● upper.

T a b l e 1. Equations representing relationship between tensile strength of alfalfa stem and moisture content and rate of loading for each height region

Treatments	Height region	Tensile strength (MPa)	R^2
Moisture content	Upper	$\sigma_t = 30.737e^{-0.015Mc}$	0.999
	Middle	$\sigma_t = 35.230e^{-0.010Mc}$	0.973
	Lower	$\sigma_t = 46.031e^{-0.006Mc}$	0.983
Rate of loading	Upper	$\sigma_t = 0.002R_L^2-0.3999\ R_L +47.922$	0.937
	Middle	$\sigma_t = 0.0029\ R_L^2-0.4971\ R_L +37.640$	0.922
	Lower	$\sigma_t = 0.0018\ R_L^2-0.4068\ R_L +30.255$	0.975

middle and lower regions, respectively, with increases in the rate of loading from 5 to 20 mm min^{-1} at the moisture content of 80% w.b. It was greater in the lower regions because of the accumulation of more mature fibres in the stem. The values of the tensile strength were significantly affected by rate of loading and the height regions, at 0.05 probability level.

CONCLUSIONS

1. The tensile strength increased exponentially with decrease in the moisture content and towards the lower regions.

2. The values of the tensile strength were within 9.24-26.35, 16.31-32.74, and 28.88-43.82 MPa for the upper, middle and lower regions, respectively, at the different moisture contents studied and at 10 mm min^{-1} rate of loading. 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 an increase in the lignin content.

3. The tensile strength increased linearly with increases in the rate of loading for all the regions. The values of tensile strength varied from 9.24 to 32.79 MPa in the upper region under 5 mm min^{-1} rate of loading and the lower region under 20 mm min^{-1} rate of loading, respectively, at the moisture content of 80% w.b.

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