Mechanical properties of rosemary (*Rosmarinus officinalis* L.) stalks

Propiedades mecánicas de los tallos de romero (*Rosmarinus officinalis* L.)

César Andrés Arévalo[1], Bernardo Castillo[1], and María Teresa Londoño[2]

ABSTRACT

Rosemary is an aromatic herb exported by Colombia. It is a perennial aromatic bush that can grow up to 2 m high. Its leaves are narrow, thin, shiny and strongly scented; the stems are woody and resinous, branched and slightly bitter. For harvesting, it should be cut manually, plant by plant, however product damage may occur during this process as the collector is pushing the branches to make the cut or when cut stems are placed in transport baskets. Tests were carried out on romero stalks to investigate the physical and rheological characteristics in order to make recommendations for harvest and post-harvest operations and to find design parameters for harvesting tools. The following rheological tests were performed: unidirectional compression, cutting, bending and tension of the bunches of stems, the manipulated structures. It was found that the compression forces that result in unrecoverable deformations are really small, approximately 2 N. The cutting force needed to fracture the bundle at the point of harvest is 30 to 50 N on average, depending on whether it is in the middle or at the base. The mechanical behavior of rosemary leaves corresponds to a viscoelastic, anisotropic and highly variable material.

Key words: rheology, uniaxial compression, tension, postharvest, handling, aromatic herbs.

RESUMEN

El romero es una hierba aromática de importancia entre las exportadas por Colombia. Es un arbusto aromático perenne, que puede crecer hasta 2 m de alto, de hojas delgadas estrechas de aspecto brillante, fuertemente perfumadas; los tallos son leñosos resinosos, ramificados y levemente amargos. Para su recolección el corte se realiza de forma manual y planta por planta; en la cosecha del romero el daño al producto se puede presentar cuando el recolector hace presión en algún brote para efectuar el corte, o cuando deposita los brotes (tallos) cortados en las canastillas de transporte. Se realizaron ensayos reológicos de compresión unidireccional, corte – flexión y tracción a los manojos de tallos que son las estructuras que se manipulan. Se realizaron ensayos a tallos de romero con el fin de investigar características físicas y reológicas y dar recomendaciones para las labores de cosecha y pos-cosecha así como para encontrar parámetros de diseño de herramientas de cosecha. Se encontró que las fuerzas de compresión que inician las deformaciones irrecuperables son muy bajas, 2 N aproximadamente. La fuerza de corte para fracturar un tallo en el sitio de cosecha es de 30 a 50 N en promedio, dependiendo de sí es en la mitad o en su base. El comportamiento mecánico de los tallos de romero corresponde a un material viscoelástico, anisotrópico y de muy alta variabilidad.

Palabras clave: reología, compresión unidireccional, tensión, poscosecha, manejo, plantas aromáticas.

Introduction

The export of Colombian fresh herbs has increased significantly in recent years, thanks to the positioning of these products in markets such as the United States and the European Community. The exportation of rosemary (*Rosmarinus officinalis* L.) from Colombia comprises 12% of total exports of herbs (Bareño and Clavijo, 2005).

Rosemary is a perennial aromatic shrub native to the coasts of the Mediterranean Sea. The plant achieves a height of 2 m, is characterized by erect, narrow, thin, glossy, strongly scented leaves (similar to eucalyptus, camphor) that are 1-3 cm long, usually grouped, coriaceous (consistency leather), green or yellowish green on the upper leaf and whitish on the underside; the stems are woody resinous, branched and slightly bitter (Sanabria, 2004).

Rosemary achieves an appropriate physiological state for harvest before blooming. Furthermore, new buds are harvested when they only have a length between 10 and 20 cm. New or young shoots that are harvested have more turgidity and hence a higher water content in the cellular structures.

Rosemary responds better to selective tip cuttings. The cutting is done manually and intensively, plant by plant.

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[1] Program of Agricultural Engineering, Department of Civil and Agricultural Engineering, Faculty of Engineering, Universidad Nacional de Colombia. Bogota (Colombia). bcastilloh@unal.edu.co

[2] External consultant. Bogota (Colombia).

Scissors that are specific to gardening are used because they prevent rips in stem tissues and thus pathogen attacks (Sanabria, 2004). The harvesting of sprouts can also be done manually (without using scissors) when the operators have the skill and experience necessary to separate the stems of rosemary plants, but this is inefficient and difficult because the stems of the plants are rigid and difficult to break. The collection container is a plastic basket with a capacity of 5 kg of fresh grass.

During collection and the further stages of handling, transport, packaging and storage, vegetable products are subject to mechanical loads of various kinds, which can cause significant damage and losses (Mohsenin, 1986; Ciro *et al.,* 2005; Singh and Reddy, 2006; Ospina *et al.,* 2007). In particular, in rosemary harvesting, product damage can occur when the collector squeezes a sprout while cutting it or when depositing cut shoots (stems) in the transport baskets.

The response of biological materials to applied loads requires knowledge of their mechanical properties, that is to say, it is essential to study rheological behavior, furthermore, mechanical behavior is one expression of the broader term of fruit and vegetable quality, that is, texture (Szczesniak, 2002; Peleg, 2006; Newman *et al.,* 2005; Bentini *et al.,* 2009).

In general terms, the mechanical behavior of any material, including organic ones, can be established from a relationship of Force *vs.* Deformation for different modes of load application (tension, compression, bending, shear, torsion), in which can be identified: parameters such as maximum force, bioyield point, point of rupture or fracture in various material tissues and the slope of the functional relationship in different ranges (stiffness or modulus of deformability) that relates the quantity of the deformation to an applied force produced according to whether the material behaves as an elastic solid, such asa viscous liquid or mixture of the two and in general with large plastic deformations (Peleg, 1987, 2006; Steffe, 1996; Buitrago *et al.,* 2004; Singh and Reddy, 2006; Aviara *et al.,* 2007).

The mechanical response of biological materials is influenced by the anatomy of the plant tissues, particularly the size of the cells, their shapes and packaging, by the thickness and strength of the cell walls and by the mechanisms of cellular adhesion together with the state of turgidity of the cells (Chanliaud *et al.,* 2002; Waldron *et al.,* 2003; Zdunek and Umeda, 2006; Oey *et al.,* 2007; Van Zeebroeck *et al.*, 2007; Toivonen and Brummell, 2008).

It has been studied extensively the rheology of fruits and some vegetables; Onion (Sagsoz and Alayunt, 2001). Lettuce (Toole *et al.,* 2000; Newman *et al.,* 2005; Martín-Diana *et al.,* 2006). Peppers (Castro *et al.,* 2007). Carrot (Ormerod *et al.,* 2004; Rastogi *et al.,* 2008). Celery (Raffo *et al.,* 2006). Pumpkin (Mayor *et al.,* 2007). Cucumber (Kohyama *et al.,* 2009). Potato (Buitrago *et al.,* 2004; Sadowska *et al.,* 2008; Bentini *et al.,* 2009). Tomato (Van Linden, 2007; Arazuri *et al.,* 2007; Van Linden *et al.,* 2008; Li *et al.,* 2010). However, studies on the mechanical properties of herbs are scarce. We found, in particular, references to the mechanical properties in tensile and shear tests of some grasses (Wright and Illius, 1995) or leaves of various plants (Lucas and Pereira, 1990; Lucas *et al.,* 1991; Choong *et al.,* 1992; King and Vincent, 1996; Aranwela *et al.,* 1999; Read and Sanson, 2003). In this regard, Niklas (1999) made an interesting review on the mechanical behavior of foliages. All these studies on the mechanical properties of herbs tried to find an explanation of the rheological behavior in terms of the characteristics of tissues and the components of cells, leaves, stems and petioles, see also Waldron *et al.* (2003).

The aim of this study was to determine the mechanical properties in compression, tension, shear and bending tests of stems (shoots), leaves and bunches of stems of freshly collected rosemary that received further handling in the packaging and marketing process.

The rheological characteristics studied here can be used as a criterion for the design of harvesting tools and packing and of methodologies for postharvest handling and transport.

Materials and methods

Plant materials

The rosemary used for the rheology testing was acquired from a specialized trading company. The tests were done on rosemary stems because this is the part of the plant that is marketed. The stems used belonged to adult plants in the full production stage. The diameters of the stems were 3 to 5 mm, which are common commercial diameters.

The literature does not report a typical number of stems in commercial presentations or the number of stems that collectors normally take in their hands while cutting. Therefore, the number of stems and the weight of the bundles chosen for testing were based on typical amounts observed in visits to crops on the Bogota Plateau.

Usually, collectors grab about six stalks of commercial crops per cut with subsequent placement in the transport containers. In addition, a typical commercial package of rosemary stems weighs 83 g. These same amounts of plant material were used in the tests mentioned below.

Rheological testing

A Stable Micro Systems® TA.XT Plus texture analyzer was used. The following tests were carried out: Unidirectional compression of 6-stalk-bundles, 50 random bundles were prepared and tested, each of 6 stems; a cylindrical probe of 75 mm in diameter was used at a speed of 2 mm s^{-1}. Unidirectional compression of 83 g bundles, 50 random bundles of stems were prepared and tested, each of 83 g; a cylindrical probe of 75 mm in diameter was used at a speed of 2 mm s^{-1}, shear and bending tests at the half-height of the stem and the base of the stem, 50 stalks were prepared for the half-height test of the stem and another 50 stems for the stem base test; a fracture wedge tool was used as a probe at a speed of 10 mm s^{-1}. Finally, tension test of one leaf and tension test of one stem, 50 trials were conducted in each case with special devices gripping the leaf and stem at a pulling tension rate of 5 mm s^{-1} in the case of leaves and 1.5 mm s^{-1} for the stems.

In all tests, a force - time curve (with strain measurement) was determined for each of the 50 bundles of stems or stem ΔL and leaf samples depending on the test (sample size). For $L$the first two and the last test, the measured deflection was converted to Hencky strain from the increase or decrease in the size of the sample ΔL (distance traveled by the probe in the compression or tensile grippers) and the initial height of the sample L with the following expressions for tension and compression, respectively:

$$\varepsilon = ln \left[1+ \frac{\Delta L}{L}\right] \tag{1}$$

$$\varepsilon = -ln \left[1- \frac{\Delta L}{L}\right] \tag{2}$$

For both compression trials, force vs. Hencky strain graphs were analyzed and, considering their shape of concavity, continuous increase up to a maximum without breaking, the typical strain was selected in which the force/deflection ratio remained straight, marking the initiation of final damage in the stem bunches; for this purpose, force and strain increases were obtained at each reading of the texturometer; subsequently, the relationship between the increase of the force and the corresponding strain was obtained to acquire the slope of the graph at each point. These tests achieved the end without rupture under a certain deformation limit through the movement of the compression tube.

Moreover, for the shear - bending and tension tests of one leaf, the average maximum force and the actual deformations at rupture (the latter only in the tensile tests) were determined. Shear – bending tests simulate the effect of scissors cutting at harvest time. With tensile testing of one stem and one leaf, the effect that collectors can exercise at any time on these organs at the time of harvest and further handling is approximated.

Results and discussion

The functional relationships (forces - Hencky Strain) obtained for the compression loading mode of bundles of 6 stalks and 83 g of stems can be seen in Fig. 1 and Fig. 2, respectively. These relationships are of the exponential or potential type with upward concavity, *i.e.* with an increasing continuous slope, which, taking into account that the deformation is corrected, indicates that the material is compressible (Peleg, 1987), that, in bundles, there is rearrangement of the stems and that, in each one, there can be a reorganization of tissues and changes in the packaging cells, possibly with the start of water flow inside them. The elastic linear portion is small and unclear, so the above procedure was used to identify the values of force and deformation at which this behavior occurs.

In Tab. 1, it can be seen that the forces in bundles that are handled in harvesting and in the stacking of boxes are very small, on the order of 2 N, although deformations are already significant. For comparison, Tab. 1 shows the maximum forces with suspended compression tests. While compression forces supported by the bunches tended to increase considerably in the range of unrecoverable deformations, need to be identified at any time the type of damage to the internal structures of rosemary leaves for each force level achieved, moreover it could not be reached rupture force value of the bundles. In particular, when dealing with groups of 6 stems, the collector exerts a gripping force on the bunch of an unknown magnitude, but typical values are cited by Wells and Greig, 2001; McGorry, 2001; Edgren *et al.,* 2004; Welcome *et al.,* 2004; Koley *et al.,* 2009; Dewangan *et al.,* 2010. These forces may vary between 50 and 300 N and are above the final test values (Fig. 1) when the Hencky strain already reached 70%, suggesting that the forces applied to the bundles as one hand holds them and the other cuts them produce high plastic deformations that should cause damage to the internal structures of rosemary leaves. In the case of 83 g bundles, stacking should not exceed contact forces of 2 N if you do not want to produce plastic deformations, though can carry loads of 35 N (Fig. 2 and Tab. 1.), but at the risk of incurring large deformations with damage not yet quantified.

Moreover, Fig. 3 and Fig. 4 show the shear and bending force variation over time of one stem, at half its height and at its base, respectively. A first maximum rupture force corresponding to the first epidermal tissue and vascular tissue of the bundles was seen which then fell slightly to the pith and then back up through the vascular tissues and with output in the epidermal tissue, according to the structure of a dicot stem. From the corresponding values presented in Tab. 1, it can be inferred that the force exercised by the collector to cut the bunch must be about 30-50 N, depending on whether the cut is made in the middle of the stem or at the base thereof, respectively, normal values for this type of manual action.

This value is very similar to that found in a shear test of ten celery petioles reported by Raffo *et al.* (2006), however the tests were performed with probes of different types and with shear and shear – bending tests. It should be noted that, according to Aranwela *et al.* (1999) and Niklas (1999), the determination of the fracture characteristics in this type of biomaterials is complex, magnitudes of the forces are relatively small, leaves are composite materials, laminated tissues and veins with a variable proportion of cellulose, hemicellulose, lignin, pectin, etc., and like the majority of biological materials, are anisotropic and viscoelastic; and the size of the biological structures in test samples has an effect.

Figure 5 shows a typical curve for the tensile strength of one leaf of rosemary, showing a stable stiffness behavior of brittle character similar to that found for leaves of grass by Wright and Illius (1995). Tab. 1 reports the average value of tensile rupture force for one leaf of rosemary, 3.5 N, similar to the values for five different types of grasses reported by Wright and Illius (1995), who attributed the tensile strength characteristics of these pasture leaves to the amounts of structural tissue, particularly sclerenchyma, which is consistent with King and Vincent (1996) and Lucas *et al.* (1991) although the latter added vascular tissue properties. In Fig. 6, it is observed that the tensile behavior of a stalk of rosemary is similar to that of a leaf, although, of course, with magnitudes greater in force but lower in Hencky strain, that is, a much greater stiffness. For this organ, the rupture force reaches 160 N on average; this value can also easily be applied by a harvesting operator. It should be added that, in both cases (leaf and stem), tension rupture is immediate.

In summary, this plant, as most biological materials including vegetables do, behaves as a nonlinear viscoelastic material, which, according to the above report by Peleg (2006), when subjected to large deformations, may suffer very important internal structural changes. Moreover, according to the values reported in Tab. 1, all tests showed high variability reflected in coefficients of variation between 22 and 65%.

At the time of collection of rosemary, the collector must manipulate stem bunches carefully, however, further studies on the damage that occurs in the stems and leaves once it reaches the all plastic strain range are recommended because it is certain that the collector will apply a force equal to or greater than this range of behavior of stem bunches of rosemary. The same advice holds for stacking bundles in containers or boxes.

Finally, it is necessary to consider that the values mentioned here do not refer to dynamic loading or impact.

TABLE 1. Maximum elastic and test force in mechanical tests of compression and maximum rupture force in shear-bending and tension testing.

Test type	Maximum force in elastic zone and maximum force test (N)	Hencky strain at maximum force in elastic zone and for test
Compression with bundles of 6 stems	1.84±0.51 11.98±6.18	0.327 ± 0.211 0.693
Compression with bundles of 83 g	2.06±0.50 36.41±10.31	0.311±0.071 0.999
	Rupture force (N)	**Hencky strain at rupture force**
Shear and bending in the middle-height of the stem	32.66±9.53	NA
Shear and bending at the stem base	47.85±12.61	NA
Tension in one stem	159.69±56.55	0.035±0.010
Tension in one leaf	3.45±1.46	0.111±0.051

The values presented are means ± standard deviation.
NA: Not available

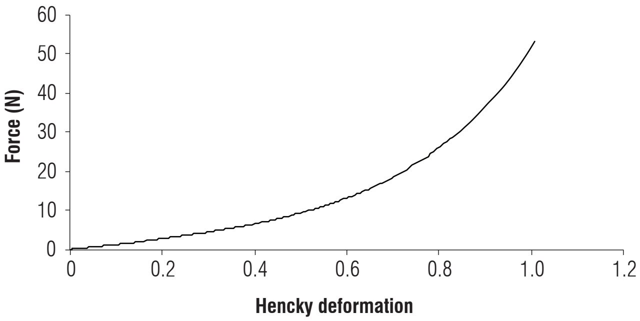

FIGURE 1. Typical force - Hencky deformation curve for unidirectional compression test with a bundle of 6 stems.

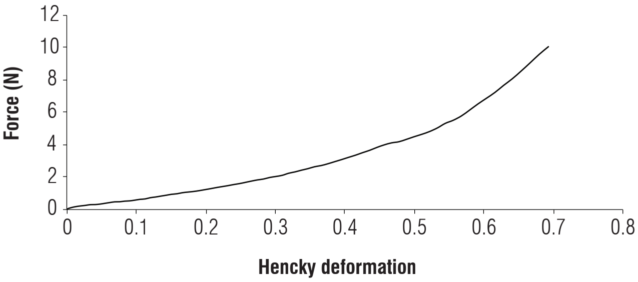

FIGURE 2. Typical force - Hencky deformation curve for unidirectional compression test with 83 g bundles.

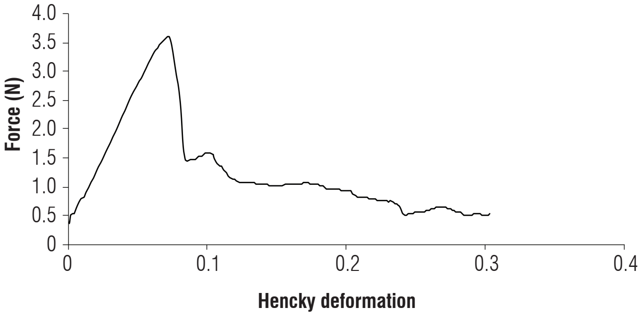

FIGURE 3. Typical force - time curve for shear - bending test in the middle-height of a stem.

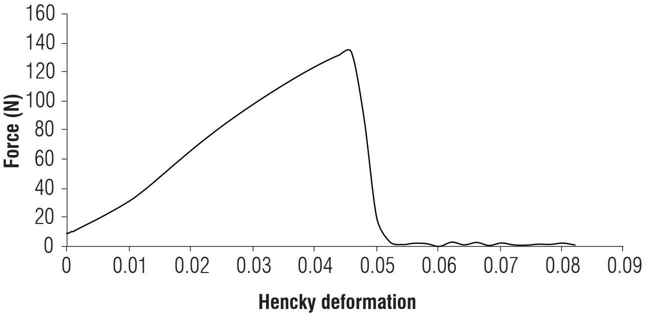

FIGURE 4. Typical force - time curve for shear and bending test at the base of a stem.

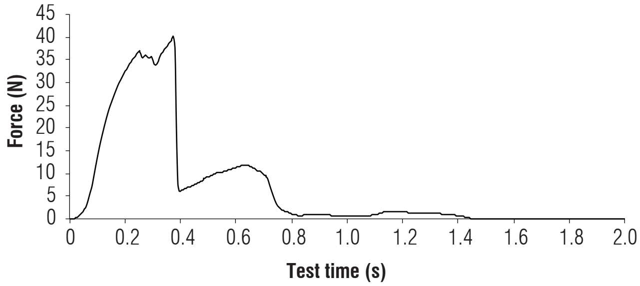

FIGURE 5. Typical force - Hencky deformation curve for tension test in one leaf.

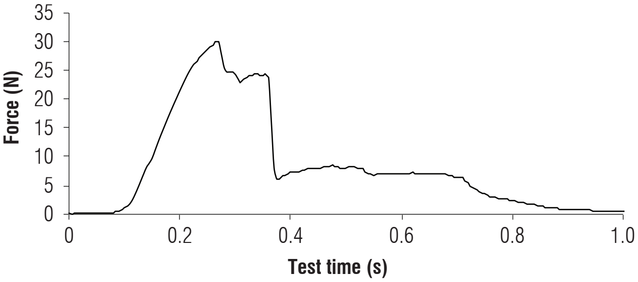

FIGURE 6. Typical force - Hencky deformation curve for tension test in one stem.

Conclusions

Rosemary stems, when subjected to quasi-static loads, behave as a viscoelastic material with high variability, anisotropic properties. The compressive forces that are withstood by stem bundles in the elastic range are very low and high irrecoverable deformations occur at the typical level of handling forces. The forces supported by the stem bundles of rosemary to shear - bending to break are between 30 and 50 N, magnitudes that are easy achieved by collectors with a common cutting device. The rigidity of rosemary stems is much higher than that of the leaves when loaded with tension.

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