Int. Agrophysics, 2004, 18,

INTERNATIONAL
Agrophysics
www.ipan.lublin.pl/int-agrophysics

Tensile strength and relaxation of tomato skin by a loop technique

*A. Rajabipour[1], M.R. Zariefard[2], G.T. Dodd [2], and E.R. Norris[2]**

[1]Faculty of Agriculture, Teheran University, Teheran, Iran
[2]Faculty of Agricultural and Environmental Sciences, MacDonald College of McGill University, 21111 Lakeshore Rd. Sainte Anne-de-Bellevue, QC, Canada

Received September 30, 2003; accepted January 19, 2004

A b s t r a c t. Two techniques of measuring tomato (*Lycopersicon esculentum* Mill. cv. New Yorker) skin strength under tension were compared. An evaluation of the standard grip technique and a new loop technique indicated that the latter showed a lower coefficient of variation for load/width, stress, and strain measured under tension. The loop technique was used to measure the effect of potassium (K) and calcium (Ca) fertilization on the skin strength of tomato fruit. Recommended levels of K and Ca resulted in the greatest skin strength, while doubling K and Ca levels, or doubling K while applying no Ca, gave rise to weaker skin. The loop technique also allowed for the determination of parameters for tensile relaxation with the Maxwell model being used to describe the viscoelastic behavior of tomato skin.

K e y w o r d s: tensile strength, relaxation, tomato skin cracking

INTRODUCTION

The role of calcium (Ca) in maintaining cell wall strength is well known. The influence of supplementation with Ca or other nutrients on fruit cracking is somewhat inconclusive. Baguskas and Geguzhaisu (1976) showed reduced cracking of hydroponically grown tomato fruit with increased P/N and Ca/N ratios of the nutrient solution, but these changes occurred in concert with variations in the K/N and Mg/N ratio of the nutrient solution. Others have also shown reduced cracking with Ca application in the field (Igbokwe *et al*., 1987; Dickinson and McCollum, 1964; Gill and Nandpuri, 1970), and under hydroponic culture (Ohta *et al*., 1993; 1994).

A number of methods for the determination of the tomato skin strength have been utilized by researchers. All the methods have encountered difficulties because of the fragility of the material.

The purposes of this work were to i) compare the newly devised loop technique to the conventional grip method in terms of its ability to measure the resistance of tomato skin to cracking, ii) investigate the effect of potassium (K) and calcium (Ca) fertilization on skin strength, and iii) investigate the relaxation characteristics of tomato skin under tension.

REVIEW OF PREVIOUS RESEARCH

An available technique of testing the strength of tomato skin is the tensile test which has been used to relate tomato skin strength, force and strain at failure, to fruit cracking. A short strip of the skin, either longitudinal (stem scar to blossom scar) or transverse, is clamped between jaws and is pulled until failure occurs (Voisey and MacDonald, 1964; Voisey and Lyall, 1965; Voisey *et al*., 1970; Batal *et al*., 1970; Hankinson and Rao, 1979; Hershko *et al*., 1994). The test was also applied to relate the epidermal strength of cherry (Levin *et al*., 1959) to fruit cracking.

Given the softness of living tissues, gripping them adequately without crushing them is one of the main difficulties in any tension test. Specimen alignment, symmetry with respect to the longitudinal axis, stress concentration, avoiding bending stress during axial loading, and other requirements, are usually specified for a tension test of materials (Mohsenin, 1986). Rubber faced jaws and a bell-shaped cutter were used by Hankinson and Rao (1979) to promote breakage near the center of the sample as opposed to at the grip itself. Hershko *et al*. (1994) used special polypropylene cloth to line the grips. However, by using an equatorial loop of skin rather than a band, many of these problems are avoided, though only transverse specimens can be analyzed.

*Corresponding author's e-mail: norris@macdonald.mcgill.ca

The strip technique has been used to measure the relaxation parameters (Hankinson and Rao, 1979). They found that the simple failure test required less time, but was not as good an indicator of cracking behavior as was the relaxation test. In their study, cultivars which resisted cracking were found to have a shorter relaxation time and a higher instantaneous modulus of elasticity (E_0). Several models have been used to characterize the viscoelastic behavior of agricultural materials. One such model is the generalized Maxwell model (Fig. 1), relating stress during relaxation to time (Mohsenin, 1986). The equation for this model is:

$$\sigma(t) = \varepsilon_0 \left[E_{d1} e^{-\frac{t}{T_1}} + E_{d2} e^{-\frac{t}{T_2}} + \ldots + E_{dn} e^{-\frac{t}{T_n}} + E_e \right] \quad (1)$$

where: $T_1, T_2, \ldots T_n$ – are relaxation times (s) corresponding to respective elements in the model, where (Fig. 1), ε_0 is the initial strain (dimensionless), $E_{d1}, E_{d2}, \ldots, E_{dn}$ are the decay moduli (Pa), E_e is the equilibrium modulus (Pa), and η_n is the material viscosity (Pa s).

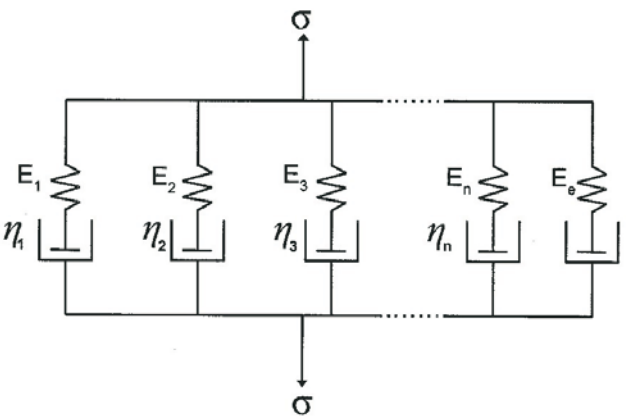

Fig. 1. Mechanical representation of the generalized Maxwell model.

To predict stress at any time *t*, one must fit the data obtained from a relaxation test to obtain $E_{d1}, E_{d2}, \ldots, E_{dn}$ and $T_1, T_2, \ldots, T_n$ under constant strain. The range of these values can then be assessed for a given set of fruits, and potentially used to compare differences among fruit subjected to different treatments. When the model is subjected to constant strain (ε_0) at time $t = 0$, the total stress, σ, is calculated as:

$$\sigma = \sigma_1 + \sigma_2 + \sigma_3 + \ldots + \sigma_n + \sigma_e \quad (2)$$

where: $\sigma = \sigma_1, \sigma_2, \sigma_3 \ldots \sigma_n$ are values of stress in elements 1,2,3 .... n (Pa), and σ_e is equilibrium stress (Pa).

The stress relaxation as a function of time can be represented by Eq. (1), which is a form of Eq. (2) in which the stresses in the elements of the Maxwell model are expressed as functions of time. The subscripts of corresponding terms of the two equations correspond to the elements of the model as shown in Fig. 1. To predict stress at any time *t*, one can fit the data gathered in the relaxation test to Eq. 1 and obtain $E_{d1}, E_{d2}, \ldots, E_{dn}$ and $T_1, T_2, \ldots, T_n$ under constant strain.

MATERIALS AND METHODS

Tomato fruit and testing equipment

Tomatoes (cv. New Yorker) were grown at the Macdonald Campus Horticulture Research Station of McGill University, Sainte Anne-de-Bellevue, QC. The full experiment consisted of four water table depth treatments (0.3, 0.6, 0.8 and 1 m depth) factorially combined with five K/Ca fertilizer treatments arranged in a randomized complete block design with 4 blocks. For the testing of tomato skin mechanical properties, only fruit grown under the optimal 0.6 m water table depth were used, and of the five K/Ca treatments only three were studied: high K, high Ca (HH); high K, low Ca (HL), and medium K, medium Ca (MM). The HH treatment received: K, 332 kg ha^{-1}; Ca, 250 kg ha^{-1} $week^{-1}$ as a 1% $CaCl_2$ solution spray. The HL treatment received: K, 332 kg ha^{-1}; Ca, none. The MM treatment, corresponding to locally recommended K and Ca application levels, received: K, 133 kg ha^{-1}; Ca, 250 kg ha^{-1} $fortnight^{-1}$. As six fruit were tested for each treatment x block, a total of 72 fruit were tested. The treatments were chosen based on the availability of sufficient fruit.

An Instron Universal Testing Machine (Series 4502), with a 500 N load cell, was used in all the experiments. The machine was connected to a computer that controlled the machine by the Instron's Series IX Automated Material Testing software (v. 5.2).

Comparison of techniques

Grip technique

For the comparison of the grip and loop techniques, 24 uniform red ripe tomatoes were obtained and 12 tomatoes were tested by each technique. For the grip technique, an equatorial loop 10 mm wide was excised with carpet knife blades, then cut perpendicular to its length to yield a single band of the same width. The ends of the specimen were held by metal clamps. The force necessary to firmly hold the specimen in this way, even with rubber or paper lining, generally crushed the clamped tissue and, under tension, many (approx. 50%) of the specimens broke at or near the grips. Crosshead speed was set at 10 mm min^{-1} and the force and displacement were recorded at the rate of five points per second. Force and displacement at failure were used to calculate load per width, stress (force at failure/cross-sectional area of the sample), and strain (change in length of specimen/specimen length before the test). The thickness of the tomato skin for cv. New Yorker (30 m) was taken from Brown (1990).

Loop technique

For the loop technique, specimens were cut around the equator of the tomato in a complete loop. To solve the problem of notches created in the edge of the tomato skin loop by simple cutting methods, a lathe was employed to cut the specimens precisely without creating edge irregularities. Two sharp carpet-knife blades, 10 mm apart, were assembled on the toolrest of a lathe; the tomato was mounted between the chuck and a live tail stock in front of the blades and turned slowly (40 rotaries per minute) to be cut. After cutting, the 10 mm wide skin loop was excised with a small hobby knife and then tested immediately. The loop was placed carefully over two parallel horizontal cylindrical bars (diameter 4 mm) on the fixed and free crosshead portions of the machine and the test begun (Fig. 2). The free crosshead moved in a way allowing alignment of the sample. Crosshead speed and data acquisition were the same as for the grip technique. Breaks generally occurred in the center of the band and rarely (<5%) at or near either of the bars.

Fig. 2. Tomato skin ready for tension test.

Effects on K and Ca fertilization on skin strength

The loop technique was used to investigate the effects of K and Ca fertilization on tomato skin mechanical properties. Three K/Ca treatments were tested. The treatments were HH, HL and MM. Loops were excised and tested from 24 fruits from each fertilizer treatment (6 replicates x 4 blocks).

Figure 3 shows a sample curve for a tension test. Skin rupture occurred at the peak of the curve. This peak was used for the calculation of mechanical properties. Forces and displacements were recorded by a computer connected to the Instron Testing Machine. Load per width, stress, and strain were then calculated. Force and displacement at failure were used to calculate load/width (load at failure divided by twice the width) and stress (force at failure divided by twice the crossectional area of the sample).

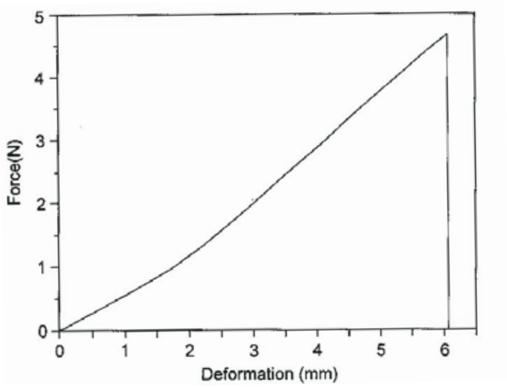

Fig. 3. Tension test of a 10 mm wide x 0.03 mm thick loop of tomato skin.

Relaxation experiments

Twenty uniform cv. New Yorker red ripe tomatoes were picked from guard rows and skin loops were obtained as above. Specimens were subjected to a ramp step function (Watts and Bilanski, 1991), The loops were subjected to increasing tension at a crosshead speed of 50 mm min^{-1} and deformed by six percent of their length (ε_0 = 6%). They were then allowed to relax for a minimum period of four minutes, while data were collected. Out of the 20 relaxation curves, the two extreme relaxation curves (Fig. 4) were fitted to the generalized Maxwell model (Eq.(1)). Different manual (Mohsenin, 1986) and numerical (Moore, 1974; Rudra, 1987; Kajuna *et al*., 1994) techniques can be used to express the relaxation curve in terms of exponential functions.

PC-MATLAB (1988) mathematical software was used to fit the data to the model. The program begins by reading

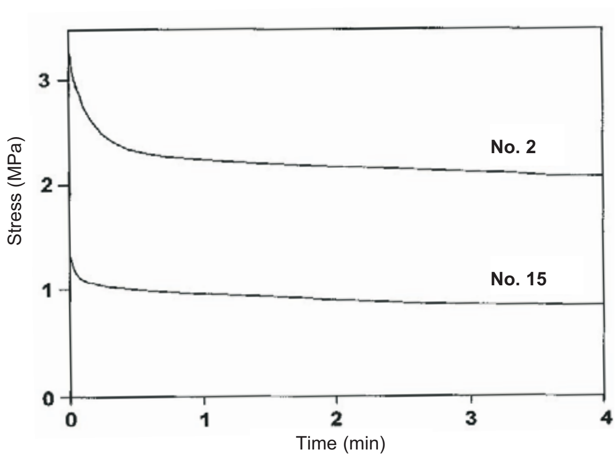

Fig. 4. Relaxation curves for two specimens, 10 mm wide x 0.03 mm thick loop of tomato skin.

initial guessed values for T_1, T_2,...,T_n and putting them into the Maxwell equation. Having these values, other parameters, E_{d1}, E_{d2},...,E_{dn}, were predicted by the least square method using the data. Error is the difference of the data values and the model values. Then a subroutine known as FMINS minimizes the error by changing the T_1, T_2,...,T_n values. The program finally returns the values for T_1, T_2,...,T_n; E_{d1}, E_{d2},...,E_{dn}, and E_e. The program has the advantage of being fast and allowing for more than 3 elements in the model.

RESULTS AND DISCUSSION

Grip vs. loop techniques

Table 1 shows a comparison of the results of tension tests done by the grip and loop techniques. The coefficients of variation for load/width, stress and strain were smaller for the loop technique. In this technique there is no stress concentration due to gripping of the tissue, therefore the results were more consistent. However, specimens can only be cut on either side of the equator. With the grip technique, all cutting orientations are possible.

Ca and K fertilization effects on skin strength

Table 2 shows the effect of Ca and K fertilizer treatments on skin strength. For the MM treatment both load/width and stress were greater than for the HL treatment, while the HH treatment was not significantly different from either of the other treatments. For strain values the treatments followed the order MM>HH>HL and were all different from one another. This trend, though not significant, did also appear for load/width and stress.

Relaxation test data were analyzed by the computer program. The model was fitted to each data set and parameters were predicted. The equation parameters for two data sets, which were the upper and lower bounds of all other data sets, are given in Table 3.

T a b l e 1. Comparison of two tension test techniques (grip *vs.* loop)

Parameter	Load/width maximum load ($N\ mm^{-1}$)		Stress at failure (MPa)		Strain at failure (%)	
	Grip	Loop	Grip	Loop	Grip	Loop
Mean	0.27	0.34	8.49	10.14	6.64	7.89
Std. dev.	0.10	0.06	2.95	1.83	2.03	1.46
Minimum	0.12	0.26	3.53	7.72	2.92	6.46
Maximum	0.45	0.46	13.42	13.65	9.40	11.44
C.V.	36.63	18.08	36.36	18.08	30.50	18.54

T a b l e 2. Effect of potassium and calcium fertilisation levels on tomato skin strength measured by the loop technique

Fertilizer applied			Load/width ($N\ mm^{-1}$)	Stress (MPa)	Strain (%)
K ($kg\ ha^{-1}$)	Ca spray interval	Treatment			
160	2 weeks	MM	0.32a*	10.72a	11.07a
400	1 week	HH	0.28ab	9.34ab	9.63b
400	no spray	HL	0.27b	8.97b	8.42c

*Means with the same letter are not significantly different at α = 0.05, Duncan's Multiple Range Test.

T a b l e 3. Relaxation model parameters

Specimen No.*	$1/T_1$	$1/T_2$	$1/T_3$	E_{d1}	E_{d2}	E_{d3}	E_e	ε_0
2	14.14	2.10	0.32	0.85	0.50	0.60	0.315	0.06
15	11.48	1.88	0.43	0.30	0.15	0.20	0.125	0.06

*See Fig. 4 for curve designations.

In terms of Eq. (1), equations fitted to the curves provided values of the parameter $T_i = \eta_i / E_i$, where η_i is the viscosity coefficient (resistance to flow) of the i-th element of the model in Fig. 1. Hence, the value of $1/T_i$ is the ratio of the modulus of elasticity (stiffness) to the viscosity of that element. Thus, a high value of $1/T_i$ or a low value of T_i implies a material with high stiffness or a low resistance to flow (or both). The relative values of these model parameters provide a useful measure of the resistance to deformation of the tomato skin as a function of time. A high value of $1/T_i$ implies a skin that is mechanically stiff with little viscous resistance. A low value implies a skin that is less mechanically stiff, but has significant viscous resistance. These preliminary results indicate the need for further study of the effects of K and Ca on the time-dependant mechanical behavior of tomato skins.

CONCLUSIONS

1. The loop method for measuring tomato skin strength showed less variability than the conventional grip method.
2. The loop method allowed relaxation tests to be done on the tomato skin, yielding values for the coefficients of the Maxwell model.
3. The effect of K and Ca fertilization on tomato skin strength parameters was investigated. Recommended levels of K and Ca yielded tomatoes with the greatest skin strength compared to those received at high levels of K and/or Ca.
4. The method could be used for testing other fruits, such as grape and peach.

ACKNOWLEDGMENTS

The authors acknowledge the financial assistance of the Natural Sciences and Engineering Research Council of Canada (NSERC). We also thank the staff of the Macdonald Campus Horticulture Research Station, and PlastiDrain Ltd. for supplying some of the pipe materials for the lysimeters in which the tomatoes were grown.

REFERENCES

Baguskas B.P. and Geguzhaisu S.S., 1976. Splits in tomatoes grown in hydroponic greenhouses (in Russian). Proc. Lenin State Academy of Agricultural Sciences, 1, 12-13.

Batal K.M., Weigle J.L., and Foley D.C., 1970. Relation of stress-strain properties of tomato skin to cracking of tomato fruit. Hort. Sci., 5, 223-227.

Brown J.W., 1990. Chilling effect on color and 1-aminocyclo-propane-l-carboxylic acid content of chilling sensitive and tolerant tomato fruit. Unpublished Ph.D. Thesis, Dep. Vegetable Crops, Cornell University, Ithaca, N.Y.

Dickinson D.B. and McCollum, J.P., 1964. The effect of calcium on cracking in tomato fruits. Proc. Amer. Soc. Hort. Sci., 84, 485-490.

Dodds G.T., Trenholm L., and Madramootoo C.A., 1996. Effects of watertable and fertilizer management on susceptibility of tomato fruit to chilling injury. J. Amer. Soc. Hort. Sci., 121, 525-530.

Gill P.S. and Nandpuri K.S., 1970. Comparative resistance to fruit cracking in tomato (*Lycopersicon esculentum* Mill.). Indian J. Agric. Sci., 40, 89-98.

Hankinson B. and Rao V.N.M., 1979. Histological and physical behaviour of tomato skins susceptible to cracking. J. Amer. Soc. Hort. Sci., 104, 577-581.

Hershko V., Rabinowitch H.D., and Nussinovitch A., 1994. Tensile characteristics of ripe tomato skin. Lebenm.-Wiss. u.-Technol., 27, 386-389.

Igbokwe P.E., Tiwari S.C., Collins J.B., and Russell L.C., 1987. Tomato cultivar response to foliar calcium and magnesium applications. J. Mississippi Acad. Sci., 32, 123-131.

Kajuna S.T.A.R., Bilanski W.R., and Mittal G.S., 1994. Characterization of stress relaxation behavior of banana plantain flesh using different models. NABEC Paper No. 94-222, Northeast Agr/Bio Engineering Conference. St Joseph, MI: ASAE.

Levin J.H., Hall C.W., and Deshmukh A.P., 1959. Physical treatment and cracking of sweet cherries. Michigan Agricultural Experiment Station Bulletin, 42, 133 pp., East Lansing, MI.

Mohsenin N.N., 1986. Physical Properties of Plant and Animal Materials. Gordon & Breach Science Publishers, New York, NY.

Moore E., 1974. Experimental fitting using integral equations. Int. J. Num. Meth. Eng., 8, 271-276.

Ohta K., Ito N., Hosoki T., Endo K., and Kajikawa O., 1993. Influence of the nutrient solution concentrations on cracking of cherry tomato fruit grown hydroponically. J. Jap. Soc. Hort. Sci., 62, 407-412.

Ohta K., Ito N., Hosoki T., Inaba K., and Bessho T., 1994. The influence of the concentration of the hydroponic nutrient culture solutions on the cracking of cherry tomato with special emphasis on water relationship. J. Jap. Soc. Hort. Sci., 62, 811-816.

PC-MATLAB, **1989.** Version 3.5g. User's Manual For MS-DOS Personal Computer. The Mathworks Inc, South Natick, MA.

Rudra R.P., 1987. A curve fitting program to stress relaxation data. Can. Agric. Engng., 29, 209-211.

Voisey P.W. and Lyall L.H., 1965. Techniques for determining the strength of tomato skins in relation to fruit cracking. Proc. Amer. Soc. Hort. Sci., 86, 597-609.

Voisey P.W., Lyall L.H., and Klock M., 1970. Tomato skin strength its measurement and relation to cracking. J. Amer. Soc. Hortic. Sci., 95, 485-488.

Voisey P.W. and MacDonald D.C., 1964. An instrument for measuring puncture resistance of fruit and vegetables. Proc. Amer. Soc. Hort. Sci., 84, 551-563.

Watts K.C. and Bilanski W.K., 1991. Stress relaxation of alfalfa under constant displacement. Transactions of the ASAE, 34, 2491-2498.