ELASTIC STRESSES AND PLASTIC DEFORMATIONS IN 'SANTA CLARA' TOMATO FRUITS CAUSED BY PACKAGE DEPENDENT COMPRESSION[1]

ADRIANA VARGAS PEREIRA[2] and ADONAI GIMENEZ CALBO[3]

ABSTRACT - The objective of this work was to study the fruit compression behavior aiming to develop new tomato packages. Deformations caused by compression forces were observed inside packages and in individual 'Santa Clara' tomato fruit. The forces applied by a transparent acrylic lever to the fruit surface caused pericarp deformation and the flattened area was proportional to the force magnitude. The deformation was associated to the reduction in the gas volume (Vg), caused by expulsion of the air from the loculus cavity and reduction in the intercellular air volume of the pericarp. As ripening advanced, smaller fractions of the Vg reduced by the compressive force were restored after the stress was relieved. The lack of complete Vg restoration was an indication of permanent plastic deformations of the stressed cells. Vg regeneration (elastic recovery) was larger in green fruits than in the red ones. The ratio between the applied force and the flattened area (flattening pressure), which depends on cell turgidity, decreased during ripening. Fruit movements associated with its depth in the container were observed during storage in a transparent glass container (495 x 355 x 220 mm). The downward movement of the fruits was larger in the top layers because these movements seem to be driven by a summation of the deformation of many fruits in all layers.

Index terms: *Lycopersicon esculentum*, mechanical damage, porosity, storage losses.

ESTRESSES ELÁSTICOS E DEFORMAÇÕES PLÁSTICAS EM FRUTOS DE TOMATEIRO 'SANTA CLARA' CAUSADOS PELA COMPRESSÃO NA EMBALAGEM

RESUMO - O objetivo deste trabalho foi avaliar a compressão dos tomates dentro das embalagens, com vistas ao desenvolvimento de novos tipos de embalagem. Deformações causadas por compressão foram observadas em frutos de tomateiro 'Santa Clara', dentro e fora da embalagem. A força aplicada com uma alavanca de acrílico transparente causou deformações no pericarpo, e a área amassada foi proporcional ao módulo da força. Essas deformações foram associadas à redução do volume gasoso do fruto (Vg), que foi expulso da cavidade locular e dos espaços intercelulares do pericarpo. À medida que o amadurecimento avançou, menores frações do Vg foram restauradas após o alívio do estresse. A falta de restauração completa do Vg foi uma indicação de deformação plástica permanente nas células estressadas. A restauração elástica do Vg foi maior nos frutos verdes do que nos frutos amadurecidos. A razão entre a força aplicada e a área amassada, a qual depende da turgidez celular, diminuiu durante o amadurecimento. Movimentos de frutos associados com a profundidade foram observados no interior de uma caixa de vidro transparente (495 x 355 x 220 mm). O movimento descendente dos frutos foi maior nas camadas superiores, porque estes movimentos são causados pela soma das deformações de frutos nas diferentes camadas.

Termos para indexação: *Lycopersicon esculentum*, danos mecânicos, porosidade, perdas por armazenamento.

INTRODUCTION

In Brazil, the traditional wooden boxes (K boxes) used to transport tomatoes (*Lycopersicon esculentum* Mill) are too deep (355 mm) and frequently cause fruit deformations, which seem not to be completely reversible. Changes in shape, soften-

---

[1] Accepted for publication on April 10, 2000.
Part of a thesis presented by the senior author to Universidade de Brasília.

[2] Agronomist, M.Sc. E-mail: vargas.a@bol.com.br

[3] Agronomist, Ph.D., Embrapa-Centro Nacional de Pesquisa de Hortaliças, Caixa Postal 218, CEP 70359-970 Brasília, DF, Brazil. E-mail: adonai@cnph.embrapa.br

ing and water soaking are common symptoms of compression stress, which cause severe losses in soft fruits such as tomatoes and strawberries (Sargent et al., 1992). Compression-induced deformations are caused by deforming components at the cellular and intercellular levels (Calbo et al., 1995).

Intercellular spaces are the main route for gas exchange in plants and their constriction by compression affects O_2 intake and other gas exchange processes. Reduction of the O_2 concentration in compressed tissues of ripe and unripe tomato fruit was observed by Calbo et al. (1995).

Sealed roots, tubers and fruits, with the internal atmosphere kept at ambient barometric pressure (9.13×10^{-2} MPa), had the air contained inside the intercellular volumes dislodged, when they were subjected to pressures above the turgor pressure (Calbo et al., 1995). Upon decompression, the elastic recovery of the cells was incomplete and the final intercellular air volume was smaller than it was before the compression stress. The data suggested plastic deformations associated with the strong adhesion among cells. Similar plastic effects over the intercellular gaseous network were also observed with the aid of the differential mass volume method in tomato fruit subjected to several linear deformations (Calbo & Nery, 1995b).

The objective of this work was to study the fruit compression behavior aiming to develop new tomato fruit packages.

MATERIAL AND METHODS

Tomato fruits (*Lycopersicon esculentum* cv. Santa Clara) produced in Brasília, DF, Brazil, were carefully harvested and brought to the postharvest laboratory at Embrapa-Centro Nacional de Pesquisa de Hortaliças in plastic boxes covered with soft plastic foam. In the laboratory, fruits were selected for freedom from defects and physiological, and pathological disorders.

The ripening index was evaluated as follows: 0- mature green fruit; 1- fruit with no more than 10% of its surface tannish-yellow (breaker); 2- fruit with 10% to 30% of its surface tannish-yellow or pink (turning); 3- fruit with 30 to 60% of its surface pink or red (pink); 4- fruit with 60 to 90% of its surface red (light red), and 5- fruit with more than 90% of its surface red. This numerical ripening index sequence is based on the USDA ripening criteria (Ryall & Lipton, 1979), which is also followed by several Brazilian 'Santa Cruz' derived tomato cultivars.

Fruit compression in the package

A glass box with a base of 495 x 220 mm and 355 mm of height was used to study fruit surface flattening, intercellular air volume deformations and changes of fruit position in the (package) box. In this assay, every layer within the box was considered one treatment, and the fruits from each layer were the replicates.

The arrangement of the fruits inside the box was aleatory, because the fruits are randomly placed inside the boxes as used in the Brazilian commercial practice.

During the storage in the glass box, the fruit flattened areas against the wall, the movement of its central point and its ripening color were recorded daily. The height between the box base and the center of the flattened figure, formed by the compression of each fruit against the wall, was used to evaluate horizontal fruit movement. This flattened ellipsoidal area (A) was estimated from its largest diameter (a) and its smallest diameter (b) using the formula $A = \pi ab/4$.

In one experiment methylene blue staining of the fruit inside the "K box" (dimensions 495 x 220 x 355 mm) was used to evaluate the number of contact areas among the fruit. An alcoholic solution of methylene blue 1 mL/L was copiously poured on the top of the box. After drying the fruit with a forced air flow, they were separated onto trays according to their layers. Only the contact areas among fruits remained unstained and the number of contact areas of each fruit were then recorded.

Elastic recovery

To study plastic deformations and the elastic recovery of tomato fruits with ripening indexes of 0, 1, 2, 3, 4 and 5, each tomato was submitted to a compression force of 4.53 N for 24 hours at 24±2°C and 68% of relative humidity in the compression apparatus (Silva & Calbo, 1992). In this assay the ripening indexes (treatments) were randomly replicated six times.

Near the end of the 24 hours-period the peduncular end of the fruit was connected to a water reservoir through a 1 mm plastic tube fixed to a 5 L pipette. The meniscus position in this pipette moved as air was absorbed or displaced by the fruit (Fig. 1). In the pipette the water was always kept closely leveled with the reservoir's water surface. At the fruit side, the pipette was filled with air at room pressure. The connection of the plastic tube to the fruit was done with a 2.5 mm diameter circular PVC plate sealed against the peduncle insertion with a plastic sealant.

After decompression, the elastic recovery was followed according to the movement of the water pulled into the pipette. A volume correction for respiration error was made with the aid of the initial 10 min respiratory baseline as previously described by Calbo & Nery (1994) and Calbo et al. (1995). This respiration baseline followed a linear pattern for more than 40 min, during which the elastic recovery was observed. For longer experimental periods, oxygen depletion in the fruit internal atmosphere resulted in anaerobic respiration. The observed water movement was caused by O_2 consumption, which occurred because the O_2 solubility in the tissues is about 30 times smaller than the CO_2 solubility (Nery & Calbo, 1994).

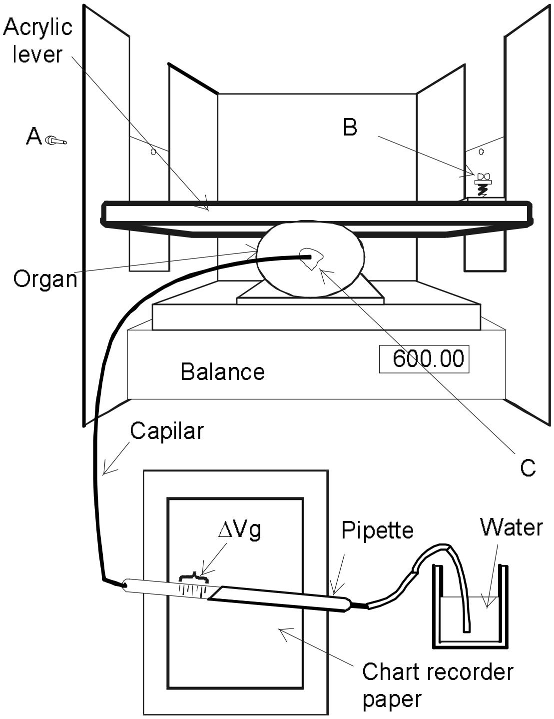

FIG. 1. Experimental arrangement to apply forces while fruit deformation was measured according to the removed air quantity. A - Acrylic lever with retaining pins to deform the fruit; B - Screw and spring for force adjustment at the acrylic lever (A), the magnitude of the force was evaluated in the balance; C - Peduncle connection for the internal atmosphere, composed of a 2.5 mm PVC disk with an attachment hole for the plastic tube externally glued to the tomato fruit by a plastic sealant.

Mass and volume of each fruit were measured before and after the assay to determine the residual plastic deformation of each fruit, assumed to be equal to the fruit intercellular air volume reduction measured by the differential mass-volume method (Calbo & Nery, 1995b).

Rapid elastic and plastic deformations

In a completely randomized assay, with 10 replicates, compression forces of 5.88, 11.76, 23.52, 29.40, 35.28, 41.16 or 47.04 N were applied to fruits with different ripening indexes using an acrylic lever placed on the top of an electronic balance (Fig. 1). Before and after compression, the fruit mass and volume were recorded for differential estimation of the plastic residual deformation, according to the changes of the remaining intercellular volume made with the differential mass-volume method (Calbo & Nery, 1995b). A 10 min respiratory baseline was also recorded for each fruit to discount the linear volumetric gaseous reduction caused by O_2 consumption (Calbo & Nery, 1994; Calbo et al., 1995).

After the application of 47.04 N, the fruit was decompressed rapidly and the elastic recuperation was observed in a pipette, in a similar way of the experiment to study elastic recovery and residual deformation after a 24 hour stress, as described above.

RESULTS AND DISCUSSION

The turgor pressure dependent firmness, i.e. ratio between the applied force and the flattened area, decreased during ripening (Fig. 2) and was independent of the applied force. Consistent with this observation, the flattened areas and the volume of gas removed, Vg, caused by fruit compression, increased with the applied force and with fruit ripening (Fig. 3).

The internal fruit deformation was divided into a plastic irreversible component and a reversible elastic component. The elastic Vg recovery was intense only during a few minutes following decompression (Fig. 4). This elastic recovery was more intense in green fruit (Fig. 5A), while intense plastic deformations indented fruit with more advanced ripening (Fig. 5B).

In fruit submitted to a 4.53 N force for 24 hours, reduced plastic and elastic deformations were observed. The differences between fruit in different ripening stages could not be demonstrated in this particular assay because the applied compression force was too small.

For fruit stored in the glass boxes, with the same dimensions as the Brazilian K box, the flattened areas of the fruit against the walls increased from the top to the bottom layers (Fig. 6A). This result was expected considering the previously observed linearity between deformation and applied load. These flattened areas increased with time during the assay, fast at the beginning and then very slowly towards the end (Fig. 6B).

The average number of flattened areas per fruit was very close to 6.0 in the whole box (Fig. 7). Fruits of the top layer had an average of only 3.5 contact areas, likewise the number of contact areas was also small in the bottom layer. In all other layers this number was approximately 6.0.

In four similar assays inside K boxes the compression force increased from the top to the bottom. However, in some cases the bottom layer, subjected to heavier load, presented more fruit, because of the natural way the fruit use the empty volumes as they fall randomly in the box. In these instances those bottom fruits were subjected to a slightly smaller compression and had a slightly smaller flattened area than the fruit from the immediately above layer.

The fruit deformation inside the static glass box caused downward movements of the fruit (Fig. 8). Downward movement was greatest for the top layer. The bottom layer height change in the flattened ellipsoid centers was negligible (Fig. 9A).

Fruit Vg as a function of layer in the packages was similar to fruit Vg as a function of force in the individual fruit assay. The box assay, however, had a poorer resolution to separate reductions in Vg caused

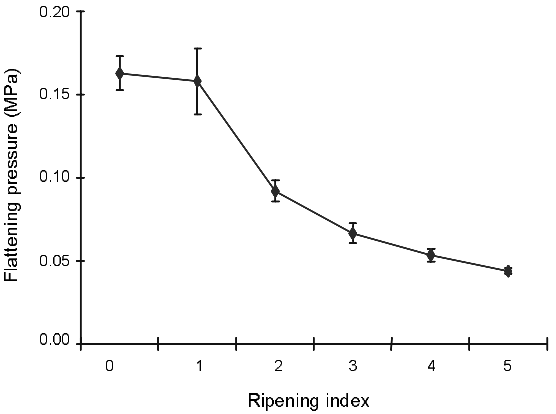

FIG. 2. Flattening pressure (MPa) of 'Santa Clara' tomato fruit submitted to a force of 47.04 N with different USDA ripening indexes during an assay at 23±2°C.

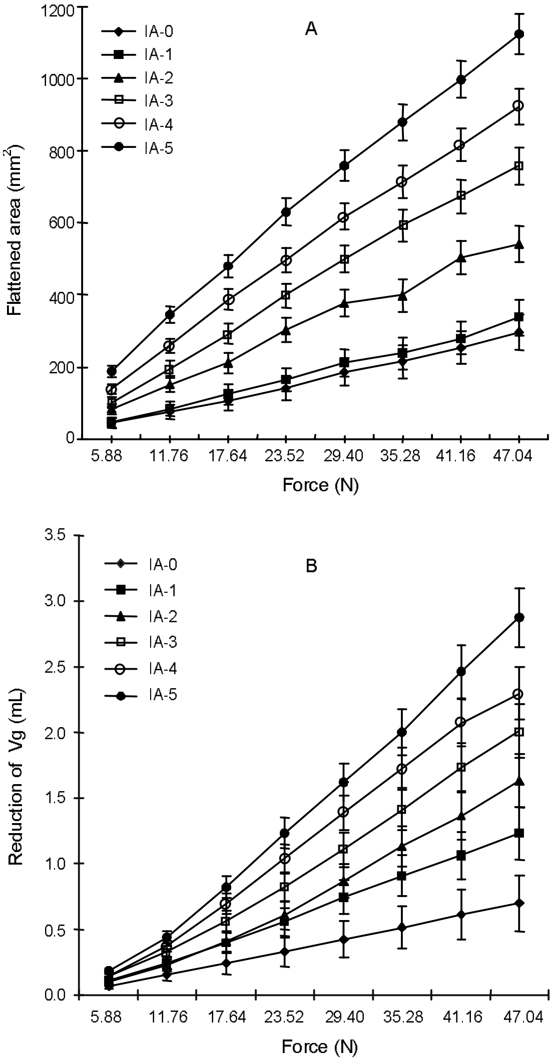

FIG. 3. Flattened area (A) and reduction of the gaseous volume (B) of 'Santa Clara' tomato fruit as a function of the applied compression force. The ripening index number (IA) followed the USDA ripening criteria. T = 23±2°C. Barometric gas pressure 91,300 Pa.

by compression. In a 13-day compression assay the plastic intercellular deformation increased towards the bottom of the box (Fig. 9B).

Similar to other tomato cultivars (Freitas, 1995; Resende, 1995; Souza, 1995), the turgor dependent firmness, measured as a ratio between the applied force and the flattened area (Calbo & Calbo, 1989; Calbo & Nery, 1995a), decreased during ripening (Fig. 2). The flattening pressure obtained for each ripening index of 'Santa Clara' tomato fruit had a magnitude similar to the turgor observed in a pressure probe study of Shackel et al. (1991) in ripening tomatoes. One possible explanation of the reduction of turgor in tomatoes during ripening is the reduction for the solute pumping from the apoplast to the simplast, which causes an increase in the concentration of solutes in the apoplast as observed by Shackel et al. (1991).

The flattened area and the Vg reduction divided by the applied force yield nearly constant ratios as a function of applied force for each ripening index. These ratios, which were indicative of the fruit susceptibility to compression, increased during ripening (Fig. 3). An explanation to this phenomenon is the expulsion of intercellular air volumes through the peduncle insertion (Fig. 4) and possibly some changes

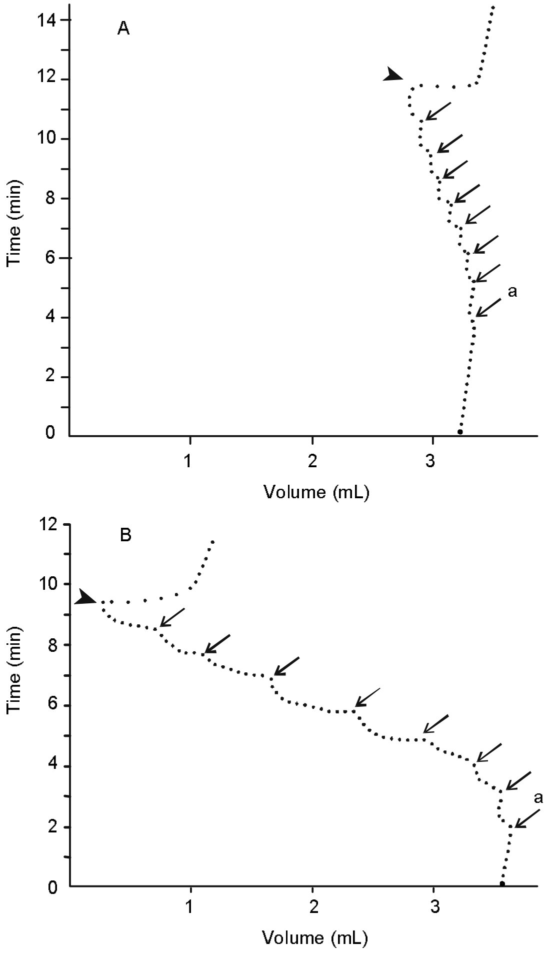

FIG. 4. Typical gas efflux from 'Santa Clara' tomato fruits submitted to increasing compression forces. Observations were made in the apparatus presented in Fig. 1. (a) start of compression. (→) Moment of addition of each 5.88 N force increment. (►) Decompression occurred after the applied force reached 47.04 N. After the end of the Vg recovery, the base line inclination caused by O_2 consumption returned to the initial value. A - mature-green fruit; B - red fruit. T = 23±2°C. Barometric gas pressure 91,300 Pa.

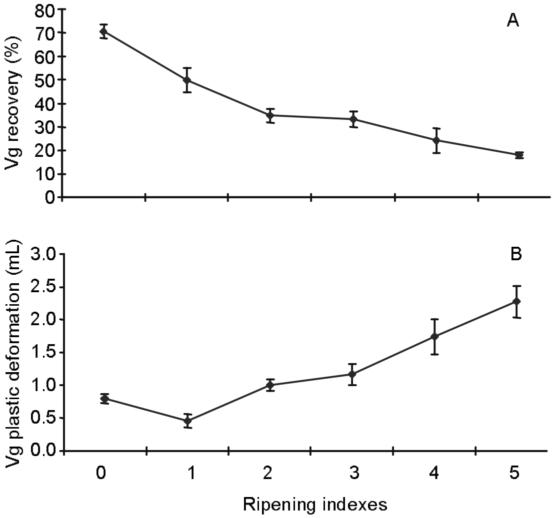

FIG. 5. Elastic gaseous volume recovery after decompression (A) and residual plastic deformation observed 24 hours after decompression of 'Santa Clara' tomato (B). Fruits with USDA ripening indexes of 0 to 5 were compressed by forces up to 47.04 N, as illustrated in Fig. 4, for this assay at T = 23±2°C. Vg = gaseous volume. Barometric gas pressure 91,300 Pa.

in the cell shape and some local water transport from compressed to uncompressed cells, as suggested by Calbo et al. (1995).

The plastic deformation of each fruit under a constant load increased with fruit ripening (Fig. 5B), while the rapid elastic fruit gaseous volume recovery was reduced during ripening (Fig. 5A). The existence of gluing components in the external surface of the cell walls facing intercellular volumes (Steckel et al., 1995) and the turgor reduction during ripening (Shackel et al., 1991) (Fig. 2) are the possible interdependent causes for the much smaller elastic gas volume recovery in red fruits.

Calbo et al. (1995) suggested that the rapid initial Vg recovery in mature-green fruits is due mainly to the locular wall movement. The methods employed to evaluate fruit deformation in the present work were not appropriate to discriminate loculus movement and pure intercellular deformation, consequently, this question remains unsolved, requiring new experimental approaches.

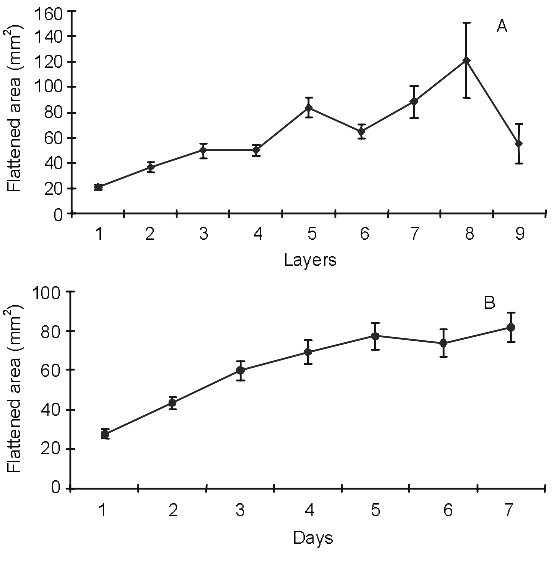

FIG. 6. **(A) Flattened area per tomato fruit (cv. Santa Clara) after 8 days of storage in a K box, pooled over days. (B) Average flattened area as a function of storage time, pooled over layers. Turning fruits usually become completely red during this assay. T = 24±2°C.**

In the assays herein reported, direct observation of sap efflux through the peduncle of compressed fruits occurred only in one case for a completely red fruit subjected to an axial compression of 47.04 N. In tomatoes transported in large trucks to the industry, similar sap efflux and localized anaerobiosis may

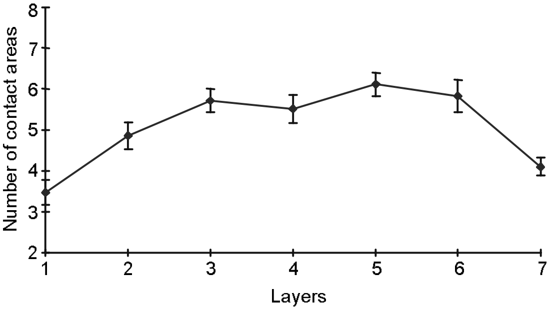

FIG. 7. **Number of surrounding tomatoes per fruit according to its layer in a wooden K box (495 x 355 x 220 mm).**

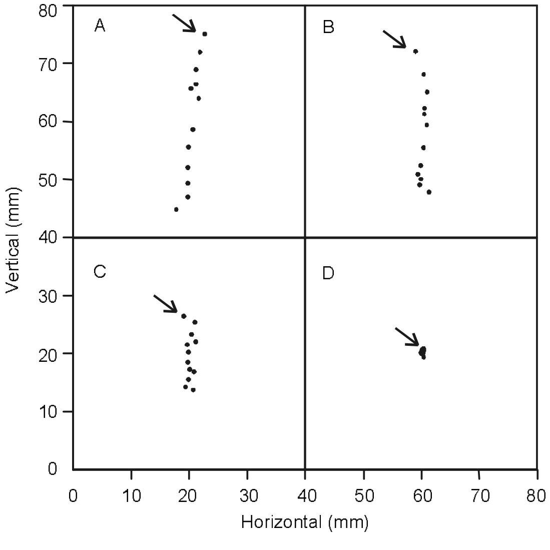

FIG. 8. **Typical movement of 'Santa Clara' tomato fruit stored in a glass box of 495 x 355 x 220 mm placed on top of a static bench at 24±2°C. Each point represents the position of the center of the flattened area on the day of the measurement. (→) Initial fruit position. A - Fruit from layer 1 (top); B - fruit from layer 3; C - fruit from layer 5; D - fruit from layer 7.**

occur with frequency, since the very ripe fruits used for canning always have high apoplasmic hydrostatic pressures, and are subjected to large estimated compression. Along this line, Calbo et al. (1995) showed that local axial compressions cause small changes in the total amount of gas contained inside tomato fruit, and large local reductions of the internal concentration of O_2. These local O_2 deprivations are caused by partial and sometimes total obstruction of the intercellular gas paths, which have their volume reduced and eventually become flooded by the dialyzed cell water.

Flattened areas of the fruits facing the walls of the glass box increased with layer depth (force) (Fig. 6A) and, at the same time, the fruit internal deformation increased, according to the fruit internal gas volume reduction (Fig. 9B). This result is a confirmation of the previous experiment and indicates irreversible internal damage in these compressed fruits.

Deformations of fruit stored in static boxes caused mainly downward movements of the fruit layers (Fig. 8 and Fig. 9A). This downward movement could, at a given layer, be considered as the summation of the deformations of the fruits in all layers below that particular one.

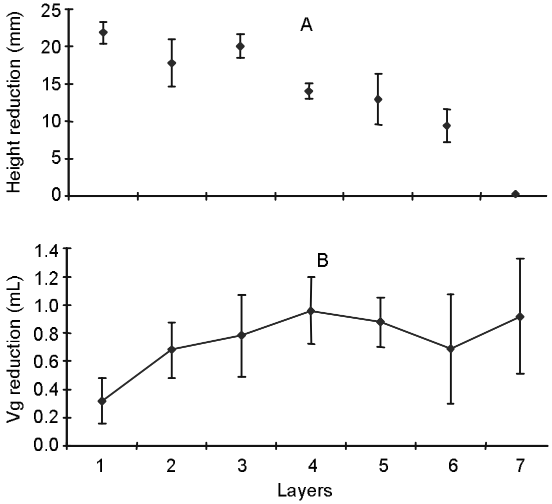

FIG. 9. Height reduction (A) and gaseous volume reduction (B) of Santa Clara tomato fruits stored in the glass box 495 x 355 x 220 mm for 13 days at 24±2°C and relative humidity of 60%. The layers were enumerated starting from the top. Vg - gaseous volume. Barometric gas pressure 91,300 Pa.

Damages caused by compression proved to be largely irreversible. Under vibrations and other causes of fruit rotation new undamaged pericarp surfaces can be exposed to compression damage. As a consequence, compression damage described in this static load study represents a lower damage limit.

CONCLUSIONS

1. For each ripening index the flattened area increases in a direct proportion to the applied force.
2. At constant applied forces the flattened area increases with fruit ripening.
3. The close proportionality between force and flattened area suggests a flattening pressure dependent on cell turgor.
4. The gaseous volume inside a tomato fruit is reduced proportionally to the compressive force.
5. The fruit capacity to recover from a deformation induced by a compression force decreases with fruit ripening.
6. Boxes with more than four layers of fruits causes irreversible fruit damage.

ACKNOWLEDGEMENTS

To CNPq, for the scholarship to the first author and the second author research grant; to Amaury Alves Nery, for the skillful laboratory assistance and firmness evaluation and for the helpful discussions; to José Luiz Oliveira da Silva, for the work in the methylene blue assay in which average flatted areas per layer and the number of fruit neighbors were evaluated.

REFERENCES

CALBO, A.G.; CALBO, M.E.R. Medição e importância do potencial de parede. **Revista Brasileira de Fisiologia Vegetal**, Brasília, v.1, n.1, 41-45, 1989.

CALBO, A.G.; NERY, A.A. A medida de firmeza pela técnica de aplanação. **Horticultura Brasileira**, Brasília, v.13, n.1, p.14-18, 1995a.

CALBO, A.G.; NERY, A.A. Methods to measure gaseous volume in plants. **Revista Brasileira de Fisiologia Vegetal**, Brasília, v.6, n.2, p.153-162, 1994.

CALBO, A.G.; NERY, A.A. Methods to measure gaseous volume of fruits and vegetables. **American Society for Horticultural Science. Journal**, Alexandria, v.120, n.2, p.217-221, 1995b.

CALBO, A.G.; NERY, A.A.; HERRMANN, P.S. de. Intercellular deformation of compressed organs. **Annals of Botany**, London, v.76, p.365-370, 1995.

FREITAS, J.A. de. **Produtividade e qualidade de frutos híbridos de tomateiro heterozigotos no loco alcobaça**. Lavras : UFLA, 1995. 86p. Dissertação de Mestrado.

NERY, A.A.; CALBO, A.G. Adapting constant volume manometry for studying gas exchange by bulky plant organs. **American Society for Horticultural Science. Journal**, Alexandria, v.119, p.6, p.1222-1229, 1994.

RESENDE, L.V. **Mecanismos de resistência a topovirus e capacidade de combinação de linhagens de tomate (*Lycopersicon esculentum* Mill) do grupo Santa Cruz**. Lavras : UFLA, 1995. 134p. Dissertação de Mestrado.

RYALL, L.A.; LIPTON, J.W. **Handling, transportation and storage of fruits and vegetables**. 1. Vegetables and melons. Westport : Avi, 1979. 587p.

SARGENT, S.A.; BRECHET, J.K.; ZOELLINER, J.J. Sensitivity of tomatoes at mature-green and breaker ripeness stages to internal bruising. **American Society for Horticultural Science. Journal**, Alexandria, v.117, n.1, p.119-123, 1992.

SHACKEL, K.A.; GREVE, C.; LABAVITCH, J.M.; AHMADI, H. Cell turgor changes associated with ripening in tomato pericarp tissue. **Plant Physiology**, Rockville, v.97, p.814-816, 1991.

SILVA, J.L.O.; CALBO, A.G. An apparatus to study compression stress in fruits and vegetables. **Pesquisa Agropecuária Brasileira**, Brasília, v.27, n.5, p.737-742, maio 1992.

SOUZA, J.C. de. **Avaliação de tomateiros híbridos portadores do alelo alcobaça em heterozigose**. Lavras : UFLA, 1995. 50p. Dissertação de Mestrado.

STECKEL, D.; RASHBASS, J.; WILLIAMS, E.D. A computer graphic simulation of squamous epithellium. **Journal of Theoretical Biology**, London, v.175, p.283-293, 1995.