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Change in strength of tomato fruit skin during ripening process

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Summary. The presented work introduces the results of the various ripeness degrees of Admiro and Encore tomato fruit varieties influence on selected mechanical properties of their skin. There were determined the strength parameters values: Young's modulus, critical compressive stress and Poisson's ratio decreased along with the achievement of full maturity by the examined fruit and were dependent on the tomato variety. Red tomato fruit skin of Encore variety, ripening at 13 °C had a higher value of Young's modulus than the skin of Admiro variety maturing under the same conditions. The highest value of Poisson's ratio was determined for the fruit with the orange-colored peel and achieved 0.73 for Admiro variety and 0.56 for the Encore fruits. The Poisson ratio lowest value, accounting for 0.47, was obtained for the red fruit skin of both cultivars ripening at 21 °C.

Key words: strength properties, tomato fruit skin, the ripening process.

INTRODUCTION

A plant material characteristic in terms of its mechanical properties is associated directly with the final product quality [22, 44]. In the case of tomato fruits the key factors deciding about their purchase are color and texture that are usually determined by using the senses but also with the instrumental measurements [6, 29]. Many instrumental methods of destructive and nondestructive character are based on force-deformation-time relationship. Such measurements results define the mechanical properties of the studied objects in terms of force, energy and pressure [12, 42, 55]. Parameters determined in a strength test are also correlated with the plant products rigidity, which being a criterion for assessing their quality and maturity before harvest, is directly related to their growth phase [17, 38]. Mechanical properties and textural characteristics of plant product are also influenced by biophysical and biochemical changes occurring as a result of maturation during storage [39, 41, 47] and devastating impact of external factors. Delicate plant material is exposed to damage in each phase of production, which is conditioned by the nature of the experienced load [16, 32, 39, 49]. Reducing raw material surface damage and maintaining high quality standards is therefore extremely important in crop production. In the case of tomato glasshouse cultivation, radial and concentric cracking of their skin pose a serious problem. Fruit showing such surface defects is characterized by the reduced shelf life and is not intended for direct consumption [11]. Therefore, the knowledge of the skin mechanical properties is of major importance not only in terms of market product quality and safety, but also for its subsequent storage, processing as well as during designing machines and devices used in manufacturing [46]. The skin of tomato fruits functions mainly as a protection of soft internal tissue against external factors. Peel is involved in growth control [2, 3] and effectively insulates the interior from the outside atmosphere, reducing thereby the gas diffusion process [1, 37, 50] as well as transport of water and other dissolved substances [10, 40, 45]. As the top layer of fruit is exposed to the greatest mechanical damage which size depends on the fruit's physiological condition. The biomechanical properties of tomato fruit skin epidermis, depending on the fruit development stage [4] and changes in the strength parameters during storage at different temperature and humidity conditions [33] were determined throughout the strength tests. Taking into account the different maturity state, tomato fruit shape and surface cracking susceptibility, the mechanical properties of the skin [3, 8, 18] and enzymatically isolated epidermal [3] were also investigated. On the basis of the puncture test carried out on various elements of the tomato fruit's internal structure hardness depending on the skin dyeing degree was determined [26], while in the compression test, among others, cracks on the surface were observed [35]. Furthermore, stiffness, the volume of strain and force required to puncture the skin were analyzed [46], as well as the strain causing fracture, deformation energy and modulus of elasticity [28].

The aim of this study was to determine Young's modulus, Poisson's ratio and critical compressive stress values by the uniaxial tensile tests application for the tomato fruit skin in a various maturity stages.

MATERIALS AND METHODS

Laboratory tests were carried out on green tomato fruits of Admiro and Encore varieties, similar in size, supplied by the Leonów Greenhouse Gardening Company in Niemce near Lublin.

The experiment was conducted on the measuring position assigned for the determination of mechanical properties of biological material [20].

Young's modulus, Poisson's ratio and critical compressive stress values were determined with the use of uniaxial tensile test. Collected from the parent plant green tomato fruits were placed in a climatic chamber at two temperatures: 13 °C and 21 °C (± 1 °C) making the need for the process of their maturation in the assumed temperature conditions. Polish Standard (1993) recommends storing tomato fruit in early dyeing stage at a temperature of 13 °C while the temperature of 21 °C simulates the natural retail and storage conditions [36].

First measurements were performed immediately after green tomato fruits were harvested and the next when their skin dyed entirely in the orange color. The study were completed at the time when the skin of fruits stored at 13 °C and 21 °C received a red color, after 28 and 12 days of storage respectively, at the assumed temperature conditions. Tomatoes were removed from the controlled environment chamber and kept in a laboratory until fruit temperature became equal to the ambient temperature. After washing and drying the fruit surface, skin specimens in the form of longitudinal strips were procured for tensile tests. The incisions were made with a profiled, single-blade knife with a limiter. Parameters such as length, width and thickness were measured before the examination.

Samples were cut from the meridional part of the fruit and had the shape of a strip with the length of 30 mm ± 0.1 mm and the width of 10 mm ± 0.1 mm. Mentioned values were measured with the use of the caliper. Thickness of each sample was measured under an optical microscope at 5 points in the central part of the strip on both sides. Thickness measurement, which was an average of 10 individual measurements, was performed with the accuracy of ± 0.05 mm.

Prepared samples were placed in clamping grips of the tensile machine, which allows constant and measurable tensile force value increase. Powdered graphite markers were randomly sprayed on the sample surface.

The method of random markers was applied to determine Young's modulus and Poisson's ratio of the tomato's fruit skin. Mentioned method relies on the image analysis and the distance between points on the sample, subjected to uniaxial stretching tests, surface [19].

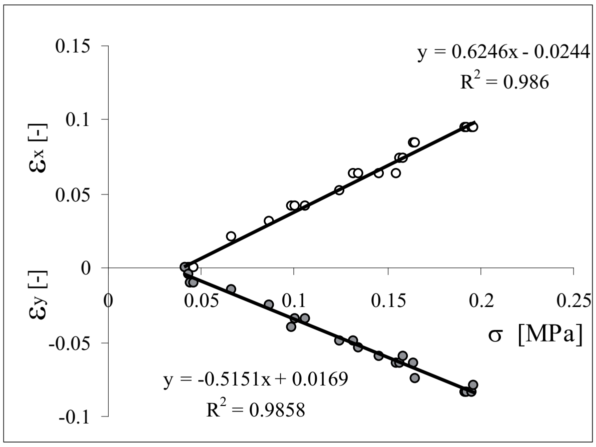

Fig. 1. Example of a dependence $\varepsilon_x(\sigma)$ and $\varepsilon_y(\sigma)$ for the stretched specimen

The main advantage of this method is that obtained results are independent of the effects observed along the specimen's edges which are close to the clamping grips of the testing machine. The random markers method allows measurements at well-defined location of the skin segment, even in case of partial damage. An additional benefit is the possibility to observe a permanent increase in strength rather than strain [19].

Each measurement series was performed in 30 replications. Young's modulus value for each sample was determined basing on the value of the straight line slope which approximated individual dependence $\varepsilon_x = f(\sigma)$ (Fig. 1), where ε_x is the relative elongation in the direction of the x-axis (-), and σ is the value of stress (MPa).

The critical surface tension of stretched specimen was determined using eq. (1), and Poisson's ratio ν was computed basing on dependence (2):

$$\sigma_k = \frac{F_z}{S}, \tag{1}$$

$$\nu = -\frac{\varepsilon_y}{\varepsilon_x}, \tag{2}$$

where: F_z – force maximum value corresponding to destruction of a sample,

S – cross-sectional area,

ε_x – relative elongation in the direction of the applied tensile force F,

ε_y – relative elongation in a perpendicular direction to the applied force F.

The total values of Young's modulus, Poisson's ratio and the critical compression stress were the averages of all individual measurements.

RESULTS AND DISSCUSSION

Conducted research indicates that the skin of tomato fruit shows no tendency to increase in strength. It was

Table 1. The average values of strength parameters determined in the study

		The tomato skin surface dyeing degree			
	Variety	Green fruits	Orange fruits	Red fruits ripening at 13 °C	Red fruits ripening at 21 °C
Young's modulus *E* [MPa]	Admiro	4.3	4.15	2.48	2.25
	Encore	5.55	5.94	4.19	2.98
Poisson's ratio *v* [-]	Admiro	0.68	0.73	0.57	0.47
	Encore	0.51	0.56	0.43	0.47
Critical compressive stress σ_k [MPa]	Admiro	0.21	0.29	0.19	0.19
	Encore	0.48	0.49	0.36	0.18

noted that with the ongoing maturation process skin becomes more fragile and susceptible to damage. Table 1 shows determined for tomato peel of both varieties being in various maturity stages, average values of Young's modulus, Poisson's ratio and critical compressive stress.

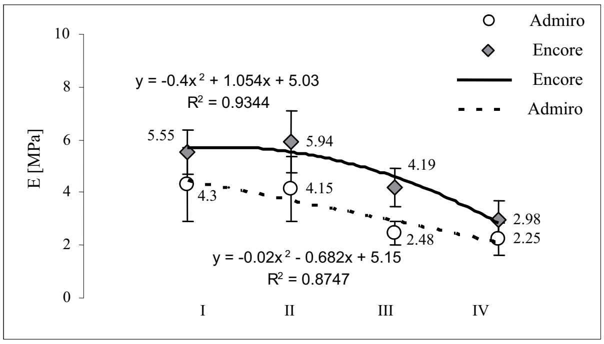

Fig. 2. The average values of Young's modulus *E* along with standard deviation determined for the skin of Admiro and Encore varieties in various stages of maturity. I - green fruits, II - orange fruits, III - red fruit maturing at 13 °C, IV - red fruit maturing at 21 °C

The value of Young's modulus decreased with the ongoing process of fruit ripening (Fig. 2). In the case of Admiro variety skin, 42 % reduction in modulus of elasticity for red fruits ripening at 13 °C compared to the value of Young's modulus determined for the skin of green fruits was observed.

Approximately 48 % lowering in the value of *E* was noticed for red fruits of mentioned variety, ripening at 21 °C in relation to the green fruits. Skin of Encore variety ripening at 13°C achieved Young's modulus value by 25 % lower (4.19 MPa) than modulus calculated for green fruit skin (5.55 MPa), while for fruit ripening at 21 °C more than 46 % decrease in *E* value was received in comparison with values received for green fruits. Red fruit maturing at 13 °C had a higher Young's modulus than those ripening at 21 °C [8, 18]. A greater difference in E values within this group of fruits, accounting for 1.21 MPa, was observed for the Encore variety while for Admiro it reached only 0.23 MPa.

Analysis of available literature proves a strong dependence of Young's modulus values determined for tomato fruit skin on the variety [2, 3, 4, 23, 24, 34, 52]. Such large variations of this parameter may indicate differences in the cellular structure of the skin and different strength properties.

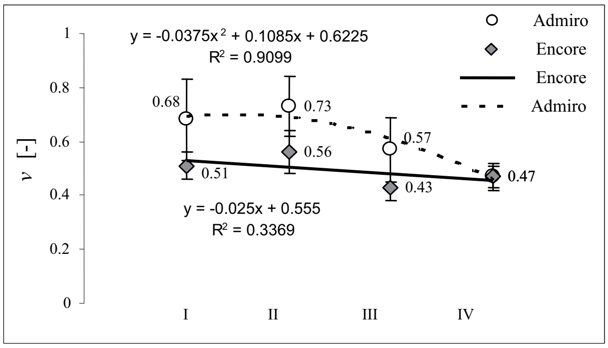

Fig. 3. The average values of Poisson's ratio *v* along with standard deviation determined for the skin of Admiro and Encore varieties in various stages of maturity. I - green fruits, II - orange fruits, III - red fruit maturing at 13 °C, IV - red fruit maturing at 21 °C

The varying maturity degrees of tomato fruit differentiate the value of Poisson's ratio (Fig. 3).

Value of Poisson's ratio for green fruit was less than in case of orange-colored skin, for which the highest value amounting to 0.73 was determined towards Admiro variety. Skin of Encore cultivar in the same state of ripeness was characterized by the Poisson's ratio value equal to 0.56 (Fig. 3). Significantly higher values of the *v* coefficient were determined for Admiro variety, however in the case of green fruits of both cultivars ripening at 21 °C the coefficient reached 0.47 [30].

Literature data indicates that the skin of examined tomato fruit cultivars was characterized by similar values of Poisson's ratio as the skin of apples [9, 21], onions [48] and broad beans [19].

The theory of elasticity [31] for isotropic 3D systems precludes the existence of materials, for which Poisson's ratio *v* exceed the value of 0.5. Using this theory, the *v* dependence on the degree of tested object isotropic dimension could be obtained [54]:

$$-1 \le \nu \le \frac{1}{D-1}. \quad (3)$$

For isotropic three-dimensional objects (D = 3) Poisson's ratio ν:

$$-1 \le \nu \le \frac{1}{2}. \quad (4)$$

However, for very thin or two-dimensional (D = 2) isotropic objects mentioned constraints change:

$$-1 \le \nu \le 1. \quad (5)$$

It should be remembered that as certain restrictions are applied only to isotropic objects. For anisotropic materials, Poisson's ratio ν can greatly exceed the limits defined by equations (4) and (5). In the theory of elasticity [5] Poisson's ratio is defined as the negative value of the deformation ε_y in a direction perpendicular to the direction of the stretching force divided by the value of the deformation ε_x in the direction consistent with the force direction. Since proposed method allows experimental determining of both: ε_x and ε_y values, there are no contraindications to use the name of Poisson's ratio, even when $\nu > 1$ [53]. Obviously using other expressions of elasticity in the case when they refer to a material with Poisson ratio $\nu > 1$ should be done very cautiously.

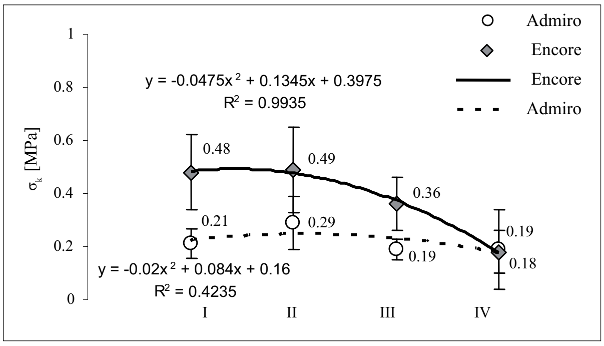

Fig. 4. The average values of critical compressive stress σ_k values along with standard deviation determined for the skin of Admiro and Encore varieties in various stages of maturity. I - green fruits, II - orange fruits, III - red fruit maturing at 13 °C, IV - red fruit maturing at 21 °C

As previously mentioned Poisson's ratio values significantly above 0.5 were observed in the different anisotropic materials, also including biological [13, 51].

For the green and orange tomato skin of Admiro and Encore varieties as well as for Admiro cultivar peel, maturing at 13 °C, Poisson's ratio was higher than 0.5 (Table 1), which means that exceeded the usually taken as a limit value for isotropic biological materials [7, 14, 43, 54]. In other cases, the value of this ratio ranged from 0.43 to 0.47. Examples of plant materials for which the value of Poisson's ratio was higher than 0.5 might be find in literature, for example for potato tissue [15], soybean hypocotyl [25], the maize root [27] and beans covers [19].

Figure 4 presents the average values of the critical compressive stress determined for examined tomato cultivars skin. With the fruits maturity increase, which was characterized by the skin red color, the critical compressive stress value decline was observed.

Encore variety tomato fruit skin was characterized by larger values of critical compressive stress in comparison to Admiro cultivar. In the case of red fruits of Encore variety ripening at 21 °C, over 62 % lower value of critical compressive stress than in case of green fruit of this cultivar was observed. For Admiro tomatoes, in contrast, σ_k depreciation amounted to only 10 %.

CONCLUSIONS

1. The strength parameters were determined: Young's modulus, Poisson's ratio and the critical compressive stress values decreased along with fruit maturity process. Green fruit skin of both cultivars was characterized by higher values of Young's modulus than the one determined for the skin of red fruits ripening at 13 °C and 21 °C.
2. The Young's modulus value depends on the tomato variety. Red fruit skin of Encore variety maturing at 13 °C had a higher Young's modulus value than the skin of Admiro fruits ripening under the same conditions.
3. The highest value of Poisson's ratio was determined for the orange-colored skin and amounted to 0.73 for Admiro and 0.56 for Encore cultivar. The lowest value of this coefficient of 0.47 was obtained for the red fruits skin of both cultivars ripening at 21 °C.
4. The critical compressive stress value determined for the skin of both tomato cultivars decreased along with achieving full maturity.
5. Ripening temperature had a dominant influence on the rate of skin dyeing. Fruits ripening at 21 °C after 12 days of storage in a climate chamber were completely stained, while those maturing at 13 °C to achieve comparable state required 4 weeks of storage.

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ZMIANA WYTRZYMAŁOSCI SKÓRKI OWOCÓW POMIDORA W TRAKCIE ICH DOJRZEWANIA

Streszczenie. W pracy zaprezentowano wyniki badań wpływu różnego stopnia dojrzałości owoców pomidora odmian Admiro i Encore na wybrane mechaniczne właściwości ich skórki. Wartości wyznaczanych parametrów wytrzymałościowych: modułu Younga, współczynnika Poissona oraz naprężenia krytycznego malały wraz z osiąganiem przez owoce stanu pełnej dojrzałości i były uzależnione od odmiany pomidora.

Skórka czerwonych owoców pomidora odmiany Encore dojrzewających w temperaturze 13 °C miała wyższą wartość modułu Younga niż skórka owoców odmiany Admiro dojrzewających w takich samych warunkach. Najwyższą wartość współczynnika Poissona wyznaczono dla owoców o pomarańczowej barwie skórki i wynosiła ona 0,73 dla odmiany Admiro i 0,56 dla odmiany Encore. Najniższą wartość współczynnika Poissona wynoszącą 0,47 uzyskano dla skórki czerwonych owoców obu badanych odmian dojrzewających w temperaturze 21 °C.

Słowa kluczowe: właściwości wytrzymałościowe, skórka owocu pomidora, proces dojrzewania.