Effects of storage duration and conditions on mechanical properties of Viola cucumber fruit under compression loading

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Abstract: In this research, the effects of storage duration and storage conditions on mechanical properties of cucumber fruit (Viola variety) were evaluated at different positions of the fruit length. The cucumber fruit mechanical properties determined in this study were firmness, apparent modulus of elasticity, failure stress, failure strain and failure energy. The mechanical properties determined under compression loading using puncture and uni-axial compression tests. The results showed that the storage duration, storage conditions and fruit test position had significant ($P<0.01$) effect on the mechanical properties of Viola cucumber fruit. The samples firmness, modulus of elasticity, failure stress and failure energy reduced about 49%, 39%, 38% and 33%, respectively during shelf life. The failure strain of samples increased 18% during storage time. Changing the mechanical properties of the cucumber fruit at room conditions was faster than refrigerator conditions. The mechanical properties were differed along the length of cucumber fruits so that near the stem region of cucumber fruit had the maximum value of firmness, modulus of elasticity, failure stress and failure energy. The sample failure strain had the minimum value at near the stem region of cucumber fruit. Among the mechanical parameters that were evaluated in this research work, the firmness can be considered as the most appropriate parameter to evaluate textural properties of Viola cucumber fruit due to significant effect of independent parameters on it and ease of usage.

Keywords: cucumber, apparent modulus of elasticity, storage, failure energy, firmness, stress, strain

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1 Introduction

Mechanical properties are important parameters to quality assessment of agro-food products. Many researchers measured mechanical properties of fruit and food products using different methods and determined different textural parameters. Applying compressive force using tension-compression machine with a cylindrical probe or compression plate tools were the most commonly methods used by the research workers. The force-deformation curve was analyzed and the features were extracted (Ghaebi et al., 2008; Hassan-Beygi et al., 2009; Pedreschi et al., 2004; Saberi-Moghadam et al., 2015; Yoshioka et al., 2009). Firmness obtained by the puncture test using cylindrical probe is one of the common test used for quality assessment of agricultural products. Failure properties such as failure stress, failure strain as well as failure energy and elastic modulus or Young's modulus are often used by engineers to evaluate the mechanical behavior of the agro-food products under the static loading too. They are correlated with the textural attributes and after firmness, these parameters are the most commonly used to estimate harvest maturity or post-harvest evaluation of fruits and vegetables texture (Abbot and Lu, 1996; Bentini et al., 2009; Singh and Reddy, 2006; Vursavuş et al., 2006). Masoudi et al. (2007) determined failure stress, failure strain, modulus of elasticity and failure energy of apple flesh samples using uni-axial compression test to evaluate texture changing of apples during storage time. Hassan-Beygi et al. (2009)

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determined firmness, modulus of elasticity, rupture force and toughness (absorbed energy to rupture point per unit volume) of apricot fruit, pit and kernel (Ordubad cultivar) using puncture and uni-axial compression tests. Saberi-Moghadam et al. (2015) determined the rupture force and toughness of the date pit (Mazafati cultivar) at different moisture content levels. The pit samples were compressed between two parallel plates until the samples ruptured.

Cucumber (*Cucumis sativus*) is a member of Cucurbitaceae family that widely cultivated. It consumes as fresh fruit, slicing, salad and pickling during all seasons. After tomato, onion and cabbage, cucumber had the fourth grade of the area under cultivation among vegetables. China, Iran, Turkey and United States produce about 66% of world cucumber production. Iran produces 1.5 million tons of various types of cucumber fruit every year (Aliabadi, 2009).

The puncture test of mesocarp (flesh) and/or endocarp (placenta in the seed cavity) as well as the uni-axial compression test of slice has been used to evaluate the textural properties of cucumber fruits. The textural properties of cucumber fruits might be varied with cultivars, time of harvest, storage period and storage conditions (Breene et al., 1972; Breene et al., 1974; Horie et al., 2004; Pevicharova and Velkov, 2007; Sakurai et al., 2005; Suojala-Ahlfors, 2005; Yoshioka et al., 2009; Yoshioka et al., 2010). Cucumber fruits with firmer texture endured 3–7 d of storage at 10 ℃-25 ℃ (Sakata et al., 2008). In cross-sectional slices of cucumber fruits, the mesocarp and endocarp are firmer near the stem end region than near the blossom end region (Breene et al., 1972; Thompson et al., 1982). Suojala-Ahlfors (2005) compared the firmness of some cultivars of cucumber fruits using the force-displacement curve of puncture test.

In spite of the high volume of cucumber fruit production in Iran, the export of cucumber fruit is not considerable. The literature survey showed that there is limited published data concerning the effects of storage duration and conditions on the mechanical properties of cucumber fruits cultivated in Iran. Therefore, the aim of this study was to determine the mechanical properties such as firmness, modulus of elasticity, failure stress, failure strain and failure energy of cucumber fruit (Viola variety) during shelf life on three positions of the fruit length at two storage conditions.

2 Materials and methods

The experiments were carried out on cucumber fruits (Viola cultivar) in July 2014, which were randomly harvested from greenhouse farms of Varamin, a city of Tehran province. The samples selected on the basis of uniformity. The mass of the samples were in the range of 82-93 g. The length and major diameter of fruit samples were in the range of 139-146 mm and 28-31 mm, respectively. All foreign materials and damaged fruits excluded manually. The fruits were stored at refrigerator ((5±2)°C and (70±3)% relative humidity) and room conditions ((25±3)°C and (35±3)% relative humidity). The experiments were done in the laboratories of Abouraihan College, University of Tehran, Pakdasht, Tehran, Iran. The required quantities of cucumber fruits that were stored at refrigerator conditions were allowed to adapt with room conditions 2 h before starting each test.

Transverse slices with 15 mm thickness cut from each fruit sample. Slice puncture and uni-axial compression tests were carried out at four storage periods (1 d, 3 d, 6 d and 9 d after harvesting time) and at two conditions of storage (room and refrigerator conditions) on three positions of the fruit (the slices were cut from near the stem end, mid-region and near the blossom end region). Each test was replicated five times. The puncture and uni-axial compression tests were done using a biological material test (BMT) device, which was developed by Ghaebi et al. (2008). The BMT device consists of three main components, which are a stable forced and moving platform, a driving unit (AC electric motor, inverter and reduction unit) and a data acquisition (load cell with resolution of 0.2 N, indicator, PC interface and software).

A cylindrical steel plunger with 3.0 mm diameter was installed on the load cell of BMT device for slice puncturing test. The slices were punctured lengthwise for a distance of 10 mm (Figure 1). At the uni-axial compression test the fruit slices were compressed about 10 mm between the two parallel plates by the BMT (Figure 2). The speed of puncturing and compression tests was 25 mm/min and the data was stored on a computer hard disk with 20 Hz sampling rate. The force–displacement curve for each sample was plotted by Excel software using the recorded data. The cucumber fruit flesh firmness was defined as the maximum force in force-displacement curve obtained by penetrating the plunger into the flesh part (Aliabadi, 2009).

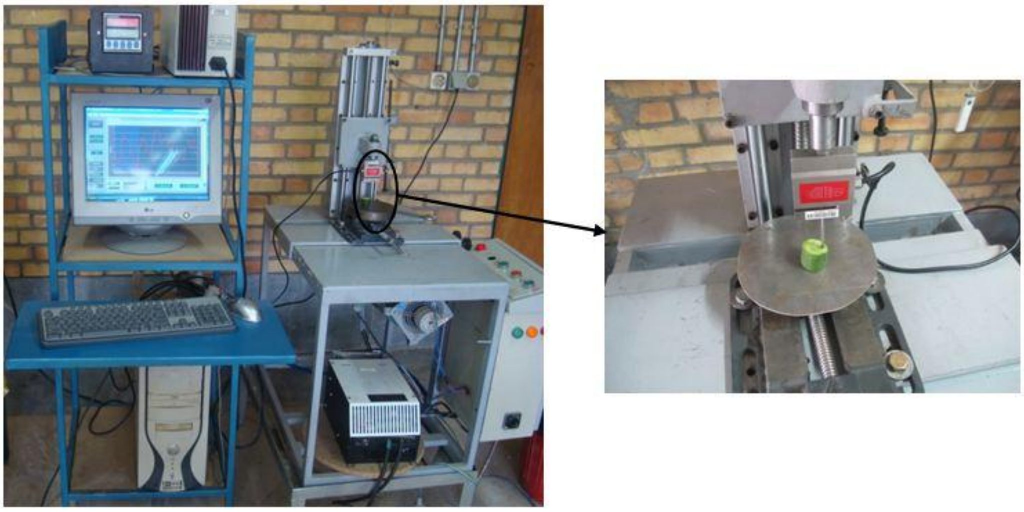

Figure 1 Slice puncture test in fleshy part of cucumber fruit

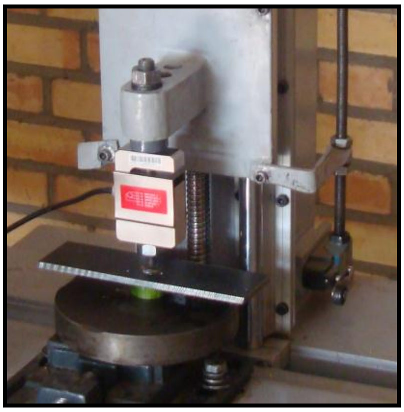

Figure 2 Uni-axial compression test for cucumber fruit slice

The cucumber apparent modulus of elasticity, failure stress, failure strain and failure energy were determined from force-displacement curve obtained in uni-axial compression test. The 50% of the failure force on the force-displacement curve (point *B* in Figure 3) named as elastic limit. The apparent modulus of elasticity was determined using Equation (1) (Abbot and Lu, 1996; Chappell and Hamann, 1968):

$$E = \frac{PL}{A\Delta L} \qquad (1)$$

where, *E* is the apparent modulus of elasticity (MPa), *P* is the elastic limit force (N), *L* is the initial length of samples (15 mm), Δ*L* is length difference before and after test at elastic limit point (mm), and *A* is the area of sample cross sectional (mm^2).

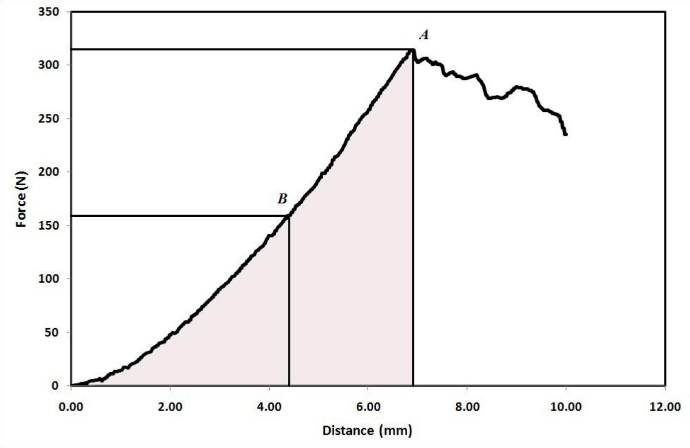

Figure 3 Cucumber slice force-displacement curve obtained from uni-axial compression test, *A*: failure point and *B*: elastic limit point

The failure stress and failure strain were determined from Equations (2) and (3), respectively (Abbot and Lu, 1996; Chappell and Hamann, 1968).

$$\sigma = \frac{4F}{\pi d^2} \quad (2)$$

$$\varepsilon = \frac{\Delta L}{L} \quad (3)$$

where, σ is the failure stress (MPa), F is the failure point force (N) (Point *A* in Figure 3), d is the diameter of the sample (mm) and ε is the failure strain (mm/mm).

Failure energy was determined from the area under force-displacement curve up to failure force (colored part in Figure 3 is the failure energy). It was assumed that the colored part is triangle and its area was calculated using Equation (4) (Masoudi et al., 2007; Hassan-Beygi et al., 2009).

$$E_{\text{failure}} = \frac{F_A \times d_A}{2} \quad (4)$$

where, E_{failure} is the failure energy (N.mm), F_A is the the failure point force (N) and d_A is the displacement at failure point force (mm).

The data was statistically analyzed using the three factors completely randomized design to study the effects of storage duration, storage conditions and fruit test positions on the firmness, apparent modulus of elasticity, failure stress, failure strain and failure energy of the Viola cucumber fruit. Further, Duncan's multiple range tests was used to compare the means. Spreadsheet software of Microsoft EXCEL 2007 and SAS 9.2 software were used to analyze the data.

3 Results and discussions

Table 1 gives the results of analysis of variance (ANOVA) for the storage duration, storage conditions and fruit test position parameters on the firmness, modulus of elasticity, failure stress, failure strain and failure energy of Viola variety cucumber fruit. As depicted from Table 1, the effects of storage duration and fruit test position were significant (P<0.01) on all the mechanical parameters. The effect of storage conditions was significant (P<0.01) on the firmness, failure strain and failure energy of cucumber fruit. The interactions of storage duration × storage conditions and storage conditions × fruit test positions were not significant on all the mechanical parameters of the cucumber fruit. The interaction of storage duration × fruit test positions as well as triple effect of storage conditions × fruit test positions × storage duration were significant only on firmness. The significant effects of independent parameters that is storage duration, storage conditions and fruit test positions on dependent parameters (firmness, modulus of elasticity, failure stress, failure strain and failure energy) will be investigated on later sentences. In all figures in this work blossom, mid and stem mean near the blossom end region, mid-region and near the stem region, respectively.

Table 1 Analysis of variance of effective parameters on some mechanical properties of Viola cucumber fruit

Source of variations	DOF	Mean sum of squares				
		Firmness, N	Modulus of elasticity, MPa	Failure stress, MPa	Failure strain, mm/mm	Failure energy, N.mm
Storage duration	3	76.35**	1.63**	0.55**	0.03**	1441676.31**
Storage conditions	1	6.33**	0.17 ns	0.06 ns	0.02**	373674.75**
Fruit test position	2	73.59**	0.51**	0.32**	0.01**	742850.90**
Storage duration × storage conditions	3	1.17 ns	0.09 ns	0.03 ns	0.00 ns	103118.10 ns
Storage duration × fruit test position	6	10.50**	0.10 ns	0.01 ns	0.00 ns	20223.14 ns
Storage conditions × fruit test position	2	0.94 ns	0.02 ns	0.00 ns	0.00 ns	1807.14 ns
Storage conditions × fruit test position ×storage duration	6	1.49*	0.01 ns	0.01 ns	0.00 ns	28088.90 ns
C.V.	-	13.21	12.28	11.75	6.65	17.62

Note: **,*stands for significant at 1% and 5% probability levels respectively, and ns means non-significant.

3.1 Firmness

Figure 4 shows the effects of storage duration, storage conditions and fruit test position on the firmness value of Viola cucumber fruit. As shown in this figure, with increasing storage duration from one to 9 d the firmness value was decreased significantly (*P*<0.01) from 7.84 N to 4.03 N; so the samples lost their firmness value 49%. The firmness value of samples kept at refrigerator conditions was more than those that were kept at room conditions significantly (*P*<0.01). It was 5.75 N for samples kept at room conditions and 6.21 N for samples kept at refrigerator conditions. Firmness was related to the test position on cucumber fruit length. It can be seen that firmness had the maximum value at near the stem end region. There was no significant (*P*>0.01) difference between mid-region and near the blossom end region. In the other words, by moving from blossom to stem end region firmness increased from 5.01 N to 7.53 N.

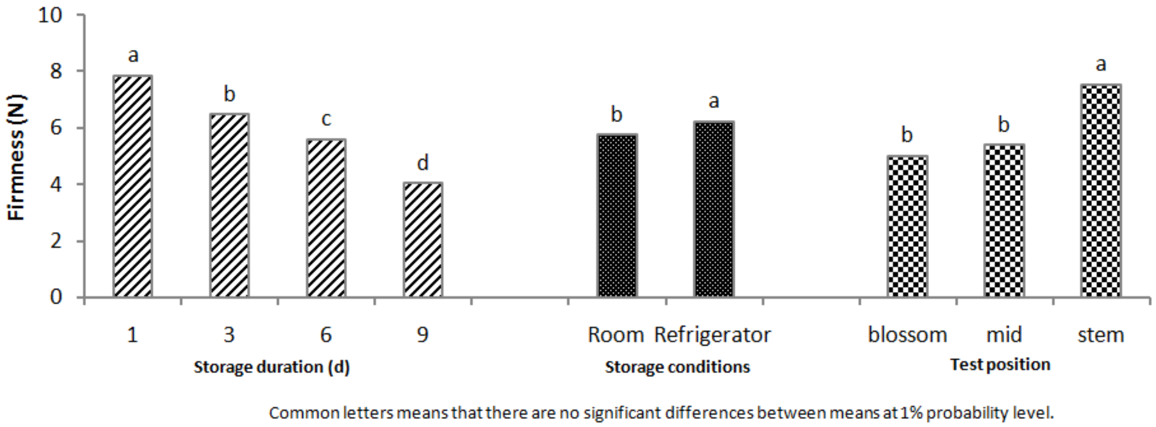

Figure 4 Effects of storage duration, storage conditions and test position on firmness of Viola cucumber fruit

3.2 Modulus of elasticity

As given in Table 1, the storage conditions had no significant effect on the fruit modulus of elasticity. Therefore, the effects of storage duration and fruit test position on the modulus of elasticity values of Viola cucumber fruit were shown in Figure 5. The modulus of elasticity was decreased significantly (*P*<0.01) with increasing storage duration from 1 d to 6 d. However, further increase in storage time from 6 d to 9 d had no significantly effect on the modulus of elasticity. The maximum and minimum values of modulus of elasticity were 1.39 MPa and 0.85 MPa, respectively, in other words the cucumber modulus of elasticity decreased 39% during shelf life. As illustrated from this figure the modulus of elasticity values for the three positions of cucumber fruit were in the range of 1.00 MPa to 1.21 MPa. The modulus of elasticity at near the stem end region was significantly (P<0.01) greater than the other regions. The modulus of elasticity at near the blossom end region and mid-region had no significant differences.

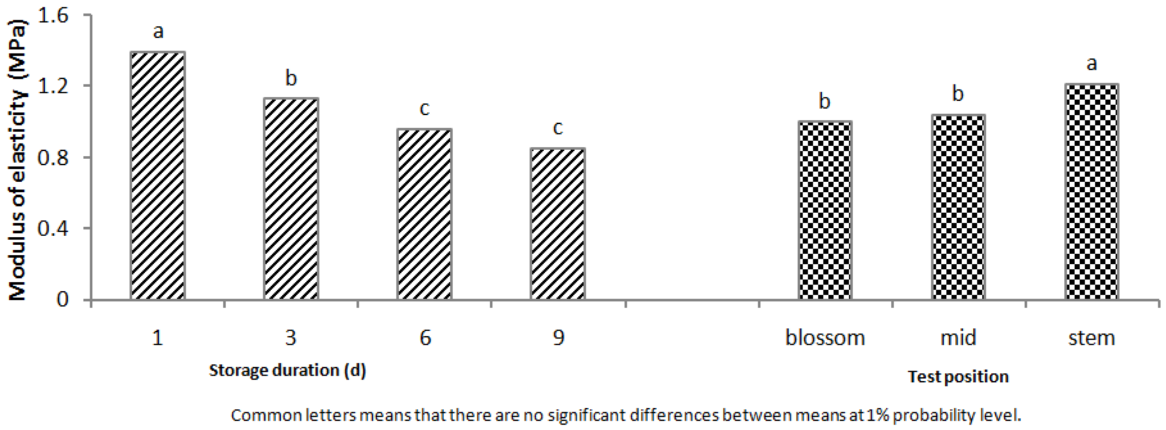

Figure 5 Effects of storage duration, storage conditions and test position on modulus of elasticity of Viola cucumber fruit

3.3 Failure stress

The storage conditions had no significant effect on the fruit failure stress (Table 1). Therefore, Figure 6 shows the effects of storage duration and fruit test position on the failure stress of Viola cucumber fruit. The failure stress value decreased significantly (P<0.01) from 0.85 MPa to 0.53 MPa (38% decrease) during 9 d of storage. The failure stress values for storage time of 3 d and 6 d as well as for storage time of 6 d and 9 d had no significant (P>0.01) differences. The failure stress values at the difference test positions of fruit were ranged from 0.61 MPa to 0.78 MPa. The failure stress at near the blossom end region and mid-region had no significant differences. However, the failure stress at near the stem end region was significantly (P<0.01) greater than other regions.

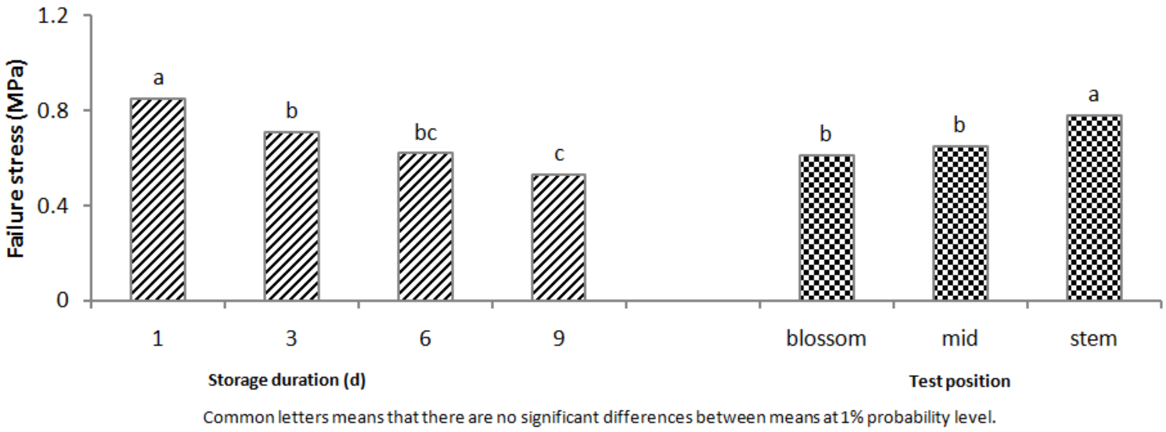

Figure 6 Effects of storage duration, storage conditions and test position on failure stress of Viola cucumber fruit

3.4 Failure strain

The effects of storage duration, storage conditions and fruit test position on the failure strain values of Viola cucumber fruit were shown in Figure 7. It can be seen from this figure that the failure strain of Viola cucumber fruit significantly (P<0.01) increased with storage duration. It increased from 0.45 mm/mm to 0.53 mm/mm during 9 d of storage (18% increase). However, there was no significant difference between the failure strain for 6 d and 9 d of storage time. Storage conditions had significant (P<0.01) effect on the failure strain of the cucumber fruit so that the samples stored at room conditions had more value of failure strain (0.51 mm/mm) compared to those kept at refrigerator (0.48 mm/mm). As depicted from Figure 7, the value of failure strain of fruit at near the blossom end region (0.51 mm/mm) had no significant difference with the failure strain at mid-region (0.5 mm/mm). However, the failure strain at near the stem end region (0.48 mm/mm) was significantly (P<0.01) smaller than those at other regions.

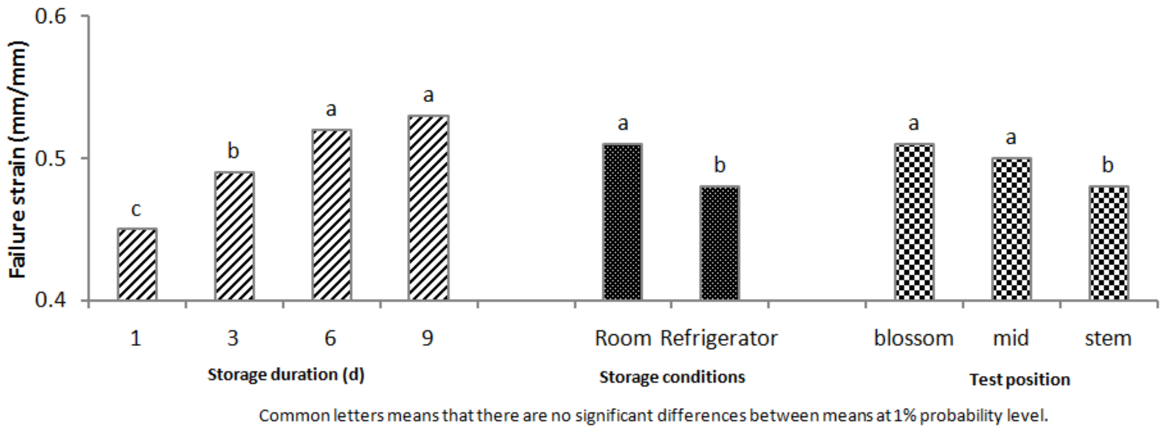

Figure 7 Effects of storage duration, storage conditions and test position on failure strain of Viola cucumber fruit

3.5 Failure energy

Figure 8 shows the effects of storage duration, storage conditions and fruit test position on the failure energy of Viola cucumber fruit. It is clear from this figure that with increasing storage duration from 1 d to 9 d the value of failure energy decreased significantly (P<0.01) in the ranges of 1482.19 N.mm to 999.91 N.mm (33% decrease). However, there was no significant difference between the fruit failure energy for 6 d and 9 d of storage time. The samples kept in refrigerator conditions had significantly (P<0.01) greater value of failure energy (1277.06 N.mm) than those kept in room conditions (1165.45 N.mm). As illustrated from Figure 8, the failure energy of the cucumber fruit was significantly related to the test position. The value of failure energy of the fruit at near the blossom end region had not significant difference with the failure energy value at mid-region. The failure energy values were 1081.52, 1228.45, 1353.79 N.mm for near the blossom end region, mid-region and near the stem end region, respectively.

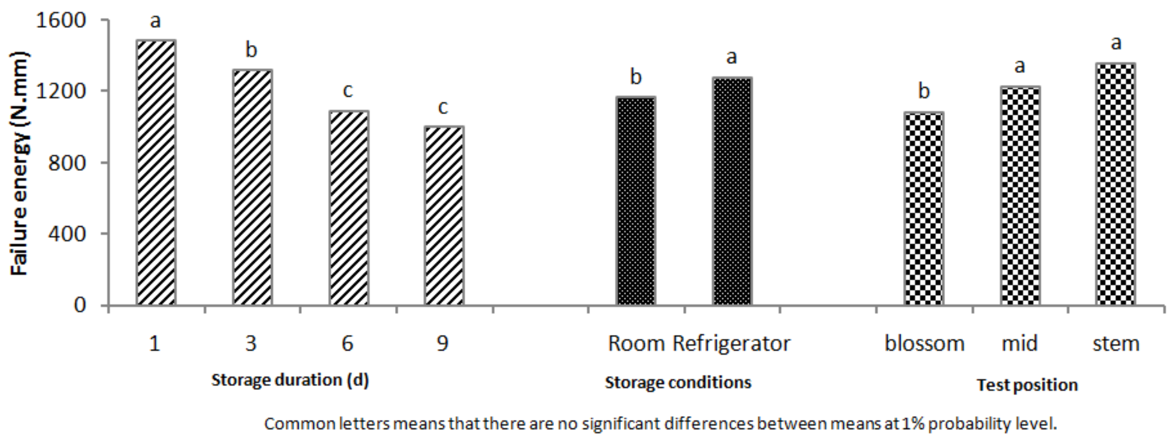

Figure 8 Effects of storage duration, storage conditions and test position on failure energy of Viola cucumber fruit

Previous research works revealed that the textural parameters of agricultural products change during shelf life as the result of water evaporation and metabolism. It can be seen from Figures 4 to 8 that with increasing storage duration the textural properties of the cucumber fruits such as firmness, modulus of elasticity, failure stress and failure energy decreased and failure strain increased. During storage time, the maximum force decreased but its position on force–displacement curve increased so the slope of stress-strain curve decreased for this reason the stress decreased and the strain increased by time passing (Zdunek et al., 2010). Firmness decreased over the time due to change the insoluble protopectin to soluble pectin and reducing the hemicelluloses (Saneheii, 1982). Research work of Singh and Reddy (2006) showed that by increasing storage duration the force and energy needed to cut the orange fruit decreased. Mirzaei Moghaddam et al. (2008), Harker and Hallet (1994) and Crisosto et al. (1999) reported that the firmness and the puncturing energy of kiwi fruits were decreased with increasing storage duration. Yurtlu and Erdogan (2005) concluded that the tissue strength of apple and pear decreased during storage duration due to decrease in the thickness of cell wall. Masoudi et al. (2007) declared that the modulus of elasticity, failure stress and failure energy of apples decreased with increasing storage duration.

The Figures 4, 7 and 8 also showed that the cucumber fruits kept in refrigerator conditions had greater firmness and failure energy and smaller failure strain than those kept in room conditions. This may be attributed to increase of evaporation, transpiration and metabolic activity of fruits kept in room conditions, which will be made the fruit texture softer due to the cellular water loss and disintegration the cell wall structure composition (Brusewitz et al., 1989). The texture of melon became softer and its modulus of elasticity and failure energy per fruit volume (toughness) decreased when increasing storage duration and storage temperature (Brummell, 2006; Gil et al., 2006; Hassan-Beygi et al., 2011). Supapvanich and Tucker (2011) for melon and Augustin et al. (1988) for muskmelon stated that the firmness is affected by storage conditions so that the firmness for samples stored at refrigerator conditions were more than those kept at room conditions. Van Hecke et al. (1998) declared that storage duration and storage methods affected the textural parameters of crisp-puffed food products. Harker and Hallett (1994) expressed that kiwi fruits stored in the air (atmosphere uncontrolled) became softer 2.6 times faster than those in controlled conditions (cold storage). Grochowicz and Nadulski (2001) reported that the firmness of apple decreased by storage temperature increasing.

As depicted from Figures 4 to 8 the cucumber fruit firmness, modulus of elasticity, failure stress and failure energy had the maximum values at near the stem end region and the minimum values at the blossom end region. By moving along the length of cucumber fruit from blossom to stem region, failure strain decreased. Breene et al. (1972) and Thompson et al. (1982) also reported that the most firmness part of cucumber fruit was near the stem end region. Hassan-Beygi et al. (2011) declared that the firmness of cantaloupe fruit had different values at different positions of fruit; it had the maximum value at middle part and the minimum value at lower part of cantaloupe. In apricot fruit, the minimum value of firmness was observed at the middle part and the firmness at upper and lower parts were nearly the same (Hassan-Beygi et al., 2009; Ghaebi et al., 2010). Sakurai et al. (2005) declared that the greatest sharpness index (that related with crispness) for Shakkito, Sharp1 and Haruno Megumi cucumber fruit varieties were at near the blossom end region. However, Viola cucumber fruit had the lowest firmness at near the blossom end region, which could be attributed to inherent differences of different cultivars of cucumber fruit or different method of evaluation. Breene et al. (1972) and Thompson et al. (1982) reported that in cucumber fruits near the stem end region have the most firmness value; their results affirm our research results.

4 Conclusions

The conclusions drawn from this research work are as follows:

(1) The effects of storage duration, storage conditions and fruit test position parameters were significant (P<0.01) on the fruit firmness, failure strain and failure energy. As well, the effects of storage duration and fruit test position were significant on the fruit modulus of elasticity and failure stress.

(2) The values obtained in puncture and uni-axial compression tests were indicative of decrease in the fruit mechanical properties (firmness, modulus of elasticity, failure stress and failure energy) with increasing storage duration. In other words, the cucumber fruit texture changed from crispy to flexible with increasing storage duration.

(3) Changing the mechanical properties of fruits were kept at room conditions were more than the fruits kept at refrigerator conditions.

(4) Near the stem end region had the maximum values of firmness, apparent modulus of elasticity, failure stress and failure energy.

(5) The firmness can be considered as the best parameter to evaluate textural properties of Viola cucumber fruit during the shelf life due to significant effect of independent parameters on it and ease of usage.

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