Determination of storage effect on mechanical properties of apples using the uniaxial compression test

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Masoudi, H., Tabatabaeefar, A. and Borghaee, A.M. 2007. **Determination of storage effect on mechanical properties of apples using the uniaxial compression test**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **49**: 3.29-3.33. The effect of storage on the mechanical properties of apples was determined over a period of six months for three export apple cultivars varieties (*malus*× domestica Borkh). A randomized design experiment with a split plot in time with nine replications was conducted and apparent modulus of elasticity, failure stress, failure strain, failure energy, and toughness were tested. An analysis of variance showed with a 1% confidence level that storage affects all the mechanical properties of apples over time. There was a significant difference at 1% probability level between the first and last month results for all properties. The mean value for all properties was higher for Granny Smith than for the other two cultivars. Golden Delicious showed higher strain and its mechanical properties decreased sharply over the first two months and the last month of storage. Red Delicious and Granny Smith showed the most uniform variation over the six months. Storage had the greatest effect on failure energy and the least effect on modulus of elasticity. **Keywords:** apple, mechanical properties, storage, uniaxial compression test.

La connaissance sure les propriétés mécaniques des pommes (Malus Domestica) est un paramètre nécessaire pour dessiner le modèle de machine de récolte et ses lignes de processus et aussi la réduction des résidues et ses pertes. Dans cette recherche on étudie les effets d'entreposage sur les propriétés mécaniques des pommes dans une période de six mois pour. trois différents cultivars utilisés pour l'exportation et cinq propriétés mécaniques dans un dessin de split plot fait au hasard avec neuf répétitions et quatre échantillonnages. Le module d'élasticité apparent, contrainte de brisure, déformation de contrainte, énergie de brisure et aussi la dureté sont déterminés pour 'Granny Smith' dans les mois du novembre jusqu'a avril. La période d'entreposage démontre un effet significatif(1%) sur les propriétés mécaniques et il y a une difference(1% level) entre le premier et le dernier temps pour toutes les propriétés. Tous les paramètres de qualité a l'etude de la 'Granny Smith' sont meilleurs que les deux autres cultivars. La 'Golden Delicious' possède une déformation plus haute que les deux autres cultivars. Les propriétés mécaniques de 'Golden Delicious' sont diminuées plus rapidement que les autres cultivars dans les deux premiers mois d'entreposage et surtout dans son dernier mois. Globalement, la 'Red Delicious' et 'Granny Smith' possèdent une variation uniforme du premier jusqu'au dernier mois de l'étude entreprise. L'entreposage a l'effet le plus grand sur l'énergie de brisure et le plus petit effet sur le module d'élasticité. **Mots clés:** pommes, propriétés mécanique, entreposage, essai de compression uni-axial.

INTRODUCTION

Unfortunately, wastage of fruits in the period between production and consumption is high in Iran (FAO 1998, 2003).

Apple prices at the time of harvest are low, inducing farmers to store the apples for sale later. Since an apple's biological and mechanical properties decrease over time, the first step to reducing waste is to improve the production-consumption cycle by studying the characteristics of the system and the crops. Mechanical properties are critical aspects of an apple's quality and knowledge of these properties helps in the development of methods for sorting apples according to firmness.

Little detailed information is available on the non-homogeneous and anisotropic mechanical properties of apples. Mohsenin et al. (1962) studied the mechanical behavior of apple fruits as related to bruising by conducting compression, impact, static load, and skin shear tests. Factors affecting the appearance of the yield and rupture points were found to be the variety, stage of fruit development, and the length of time during which force was applied. They found that the more ripe the fruit, the more permanent (plastic) deformation.

While skin failure occurs at the time of harvest, an apple is more sensitive to bruises one to two weeks after harvest. As the fruit ripens, the compression force or stress required for deformation declines. Mohsenin et al. (1963) used an engineering approach to evaluate textural factors in fruits and vegetables. They determined the modulus of elasticity of apples using a uniaxial compression test. The results showed that the modulus of elasticity reached its highest value at or before the conventional time of harvest. It also had the largest rate of change and the most consistent behavior of any other physical or mechanical property investigated.

Chappell and Hamann (1968) examined the behavior of three varieties of apple flesh at harvest using a constant–stress creep test and determined Poisson's ratio and the initial compressive Young's modulus for each variety and stress level. All three varieties had a modulus of elasticity that was significantly stress dependant. Mohsenin (1986) examined the calculation of modulus of deformability for apples using penetration and parallel plate loading tests. The mean value of modulus of deformability by the Hertz theory for elasticity was 1.85 MPa. By the conventional method of compressing a cylindrical specimen of the flesh between two parallel plates, it was 1.70 MPa.

Abbott and Lu (1996) determined the effects of ripeness, specimen orientation, and location within the apple on failure stress, strain, energy, and apparent modulus of elasticity (Young's modulus). Compression tests were performed on

Golden Delicious, Red Delicious, and Rome Beauty apples using a Universal Testing Machine. The four mechanical properties were significantly influenced by specimen orientation, latitude, depth, and, to a smaller extent, by orientation-latitude, orientation-depth, and ripeness-depth interactions. The other interactions were either quite small or not significant. Failure stress was highest in the vertical direction and lowest in the tangential direction. Young's modulus was significantly higher in radial samples than in tangential and vertical samples. The largest values of failure stress and Young's modulus were obtained from the bottom sections and the smallest Young's modulus value from the top sections. Red Delicious apples varied more around their circumference than did Golden Delicious and Rome Beauty apples. The anisotropic properties of the apples were more pronounced in the middle (equatorial) sections than in the top (stem) or bottom (calyx) sections. Sunnyside Red Delicious apples had higher values of all properties than the shade side.

No previous studies were conducted investigating the effect of long term storage on the mechanical properties of apples. The objective of this study was to determine the effects of storage on mechanical properties of *malus domestica*. Uniaxial compression tests were performed on Golden Delicious, Red Delicious, and Granny Smith apples using a Universal Testing Machine.

MATERIALS and METHODS

The three cultivars of Golden Delicious, Red Delicious, and Granny Smith apples were selected because of long storage life and export quality. All samples were randomly selected from Sorkdashat Damavand Company (Damavand City, Iran) cold storage at the beginning of October 2003. The apple boxes were transferred to cold storage in the College of Agriculture, University of Tehran, Karaj, Iran. These samples were placed in wooden boxes placed next to one another and stored at 4 to 5°C with 65 to 70% relative humidity. Six series of tests were done on samples beginning after two months of cold storage. Before each test series, the sample was transferred to the department laboratory and placed at 20 to 22°C temperature for 24 hours.

For all test series, the dry bulb temperature and relative humidity of the laboratory were recoded using a digital recorder (5100 Model, Barloworld Scientific Ltd T/As Jenway,, Dummow, Essex, England) as shown in Table 1. These parameters were measured at 9 am, 12 pm, and 3 pm and then averaged.

The moisture content of the apples was measured by cutting nine apples selected at random. The samples were weighed using a scale with 0.1 g accuracy, placed in an aluminum box, and positioned inside an electrical oven for 10 days at 77°C. The moisture content was determined using the weight of the apple samples before and after drying and the weight of the empty box using the standard wet-basis moisture content equation.

Uniaxial compression tests on apple flesh samples were done on a Universal Testing Machine (HTE Model, Hounsfield Company, Surrey, England) with a maximum loading sense of 5 kN, in the Agricultural Engineering Research Institute (AERI) laboratory, Karaj, Iran. Samples were prepared as in Bajema et al. (1998). Four equidistant points on the circumference of each apple were numbered from one to four. A sampler cylinder with a 10 mm interior diameter and 100 mm length was constructed and installed on an electric drill. Each sample was taken by pushing the apple 40 mm onto the sampler cylinder toward the drill at the selected point. The sample was then forced out of the sampler using air pressure and was placed in an apple flesh holder and reduced to 15 mm in length using a sharp knife. Nine apples of each type were tested, making 108 samples per test series and a total of 648 samples over the six test series.

Samples for each series were simultaneously loaded between the two parallel plates of the Universal Testing Machine and their force-deformation curves were recorded by computer. From these curves, the apparent modulus of elasticity, failure strain, failure stress, failure energy, and toughness were determined and calculated. Loading rate was kept constant at 25.4 mm/min. Maximum loading length was 8 mm. The apparent modulus of elasticity was determined at 50% of the yielding point force on the force-deformation curves (point B), as in Abbott and Lu (1996), from Hooke's law and Eq.1 (Chappell and Hamann 1968).

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

where:
E = modulus of elasticity (MPa),
F = elastic limit force (N),
L = initial length of samples (15 mm),
ΔL = length difference before and after test (mm), and
A = average sample cross sectional area (mm^2).

Failure stress was determined by:

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

where:
σ = failure stress (Mpa) and
d = diameter of sample (mm).

Failure strain was determined by:

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

where ε = failure strain.

Failure energy was measured from the area under the force-deformation curve. This area was selected using Adobe Photoshop Version 7.0 Software and was determined using an area meter program. Toughness equaled failure energy divided by apple flesh sample volume.

Table 2. Moisture content (wet basis) of apples.

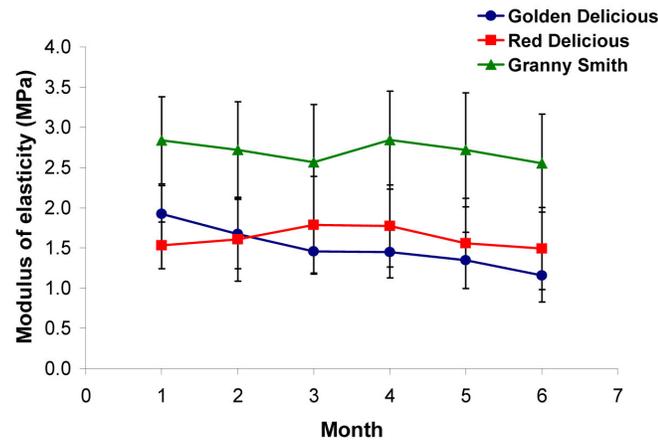| Test series	Golden Delicious (%)	Red Delicious (%)	Granny Smith (%)
1	82.12	83.20	83.34
2	83.94	84.21	84.14
3	82.92	83.82	84.37
4	84.49	83.75	84.20
5	84.69	84.38	83.10
6	84.54	83.80	82.87

Fig. 1. Apparent modulus of elasticity of cultivars over six test series (vertical bars indicate the SD of means, n = 36).

A split plot in time with a randomized design using nine replications and four samplings was conducted. The treatments were the six time series with the three cultivars of apple as independent variables. Modulus of elasticity, failure stress, failure strain, failure energy, and toughness for Golden Delicious, Red Delicious, and Granny Smith in different test series from December, January, February, March, April, and May were determined and analyzed using the ANOVA (SAS V.8, SAS Institute Inc., Cary, NC) program.

RESULTS

Table 2 shows that the moisture content for all three cultivars was similar for the six test series. Golden Delicious apples showed a negligible 1 to 2% moisture gain over the several months of the study.

Apparent modulus of elasticity

Variation of the apparent modulus of elasticity over the six test series is shown in Fig. 1. The modulus of elasticity for all the three cultivars shows a decreasing trend, with Granny Smith showing a higher modulus of elasticity than the other two cultivars. The Granny Smith modulus of elasticity for the first test series was 2.84 MPa, which decreased to 2.56 MPa in the third test series, increased to 2.84 MPa for the fourth test series (a 10% increase) and then again decreased to 2.55 MPa in the last test series. Thus, for the Granny Smith apple, six months of storage had an effect of 10% on the modulus of elasticity. Strength variation for Granny Smith was higher and more flexible.

For Red Delicious, the modulus of elasticity in the first test series was 1.53 MPa, which increased over the next three test series and then decreased again to 1.49 MPa. Red Delicious showed more uniformity over the several months of storage.

The Golden Delicious modulus of elasticity ranged from 1.92 to 1.16 MPa in a decreasing manner. The modulus of elasticity for the first and last test series shower a significant difference. This range of values was also reported by Mohsenin (1986) and Abbot and Lu (1996). Abbot and Lu (1996) showed that ripeness will reduce the mechanical parameters over time, so it can be assumed that the apples have ripened during storage.

Apparent modulus of elasticity was determined using the analysis of variance for the time of the test series, cultivars, and the interactions between them as shown in Table 3. There was a significant effect on the modulus of elasticity at the 1% confidence level.

Failure stress

Variation of failure stress during the storage is shown in Fig. 2. It is obvious that the stress decreases over the time of storage. Failure stress for the Golden Delicious was 0.28 MPa in the first test series and 0.11 MPa in the sixth test series. The
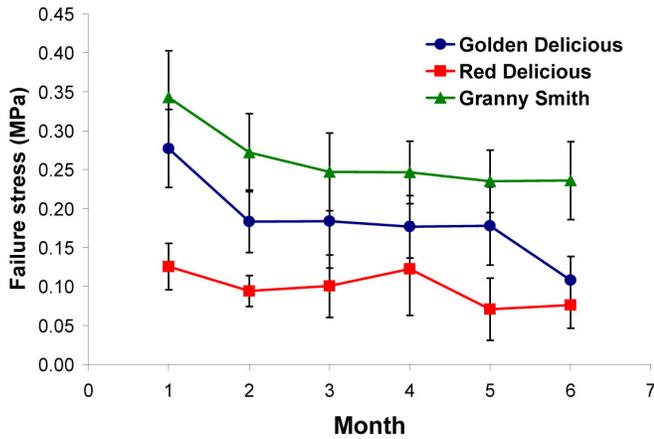
Table 3. Analysis of variance for all mechanical properties of apples.

Source	Degrees of freedom	Mean square				
		Modulus of elasticity	Failure stress	Failure strain	Failure energy	Toughness
Cultivar	2	94.556*	1.461*	143.600*	5896.614*	0.004*
Error	24	0.672	0.005	22.014	26.473	0.00002
Time of test series	5	1.779*	0.141*	68.780*	607.964*	0.0004*
Cultivar time	10	0.960*	0.021*	21.350*	116.278*	0.00008*
Experimental error	119	0.380	0.005	7.756	30.269	0.00002
Sampling error	480	0.207	0.001	2.287	7.807	0.000006
Total	640					
CV (%)		23.429	18.635	16.656	30.081	30.442

* Significant at 1% probability level

Note: The number of missing values was 7 and variables are consistent with respect to the presence or absence of missing values.

Fig. 2. Failure stress of cultivars over six test series (vertical bars indicate the SD of means, n = 36).

Golden Delicious failure stress decreased more sharply between the first and second and fifth and sixth test series.

Failure stress for Red Delicious was 0.13 MPa in the first test series and 0.08 MPa in the sixth test series. Red Delicious failure stress decreased in the first test series and then increased to 0.13 MPa by the fourth test series.

Granny Smith hasd the highest values of failure stress, changing from 0.34 to 0.24 MPa from the first to last test series. In the first test series, it increased 17.5% over Golden Delicious and 61% over Red Delicious. Failure stress decreases over time, as shown by Mohsenin et al. (1962).

Analysis of variance was applied to failure stress over the cultivar, time of test series, and interactions between them as shown in Table 3. They had a significant effect on failure stress at the 1% confidence level.

Failure strain

Figure 3 shows the variation of failure strain over the six test series. Strain decreased during storage. Golden Delicious failure strain was greater than for the other two cultivars at 13% in the first test series and 9.4% in the last. This decreasing trend was not as smooth as for the other cultivars.

Red Delicious apple failure strain showed the smallest decrease at 7.7% in the first test series and 5.5% in the sixth.
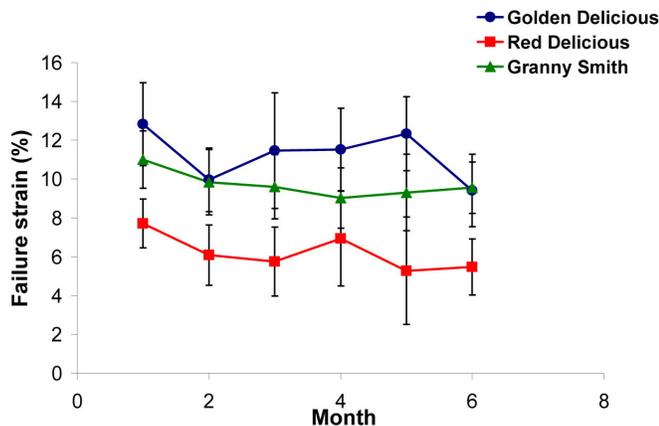

Fig. 3. Failure strain of cultivars over six test series (vertical bars indicate the SD of means, n = 36).
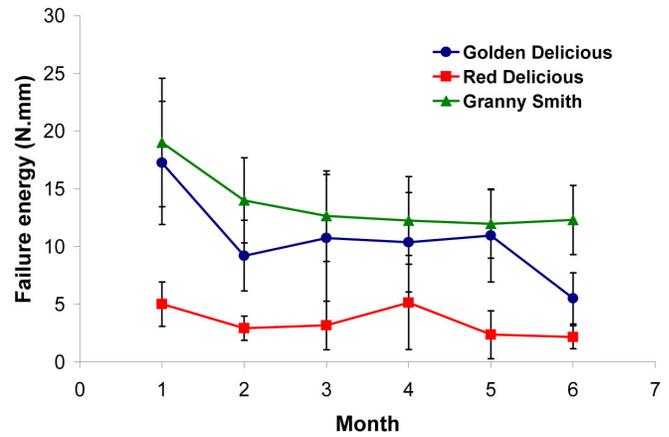
Granny Smith failure strain was 11% in the first test series and 9.5% in the sixth. Granny Smith had a more uniform decrease in failure strain than did the other two cultivars.

The analysis of variance for failure strain and the other treatments (cultivar, time of test series, and interactions) is shown in Table 3. The time of test, cultivar, and the interaction between them was significant for failure strain at the 1% confidence level.

Failure energy

Variations of failure energy over the six test series has been graphed in Fig. 4. Granny Smith apple failure energy was higher than for the other two cultivars. The failure energy of this cultivar was 19 N.mm in the first test series and 12.3 N.mm in the last, with the first two test series showing a sharper decrease than for the other series. Golden Delicious apple failure energy in the first test was 17 N.mm and 5.5 N.mm for the last, however, the trend variation was not very uniform. Red Delicious had a very small failure energy variation; 5 N.mm in the first and 2.9 N.mm in the last test series. For Granny Smith, six months of storage led to a 35% decrease in energy of failure. These results are the same as found by Abbot and Lu (1996).

The analysis of variances for the cultivar, time of test series, and the interactions between them is shown in Table 3. They were significant for failure energy at the 1% confidence level.

Toughness

Variation of toughness over the six test series is shown in Fig. 5. Granny Smith had the highest toughness with 0.016 mJ/mm^3 in the first test series and 0.01 mJ/mm^3 in the last. The first two test series showed a sharper decrease than for the other test series. Golden Delicious toughness for the first test series was 0.015 mJ/mm^3 and 0.005 mJ/mm^3 for the last test series, however, the variations were not uniform. Red Delicious apples had a very small toughness variation of 0.004 mJ/mm^3 over the test series.

Analysis of variance for variation in toughness for the cultivar, time of test series, position, and interactions between them are shown in Table 3. The cultivar, time of test, and the interaction between them has a significant effect on toughness at the 1% confidence level.
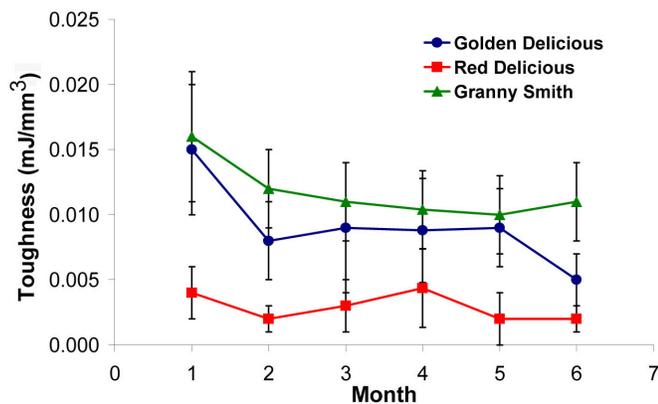

Fig. 4. Failure energy of cultivars over six test series (vertical bars indicate the SD of means, n = 36).

Fig. 5. Trend of cultivars toughness over six test series (vertical bars indicate the SD of means, n = 36).

A mean comparison of all mechanical properties showed that all parameters were significantly different at the 5% confidence level, with the mean value of all the parameters for Granny Smith being higher than for the other cultivars. Thus, this cultivar will have higher strength against mechanical harvest, impact, and transportation vibration. Golden Delicious had the lowest value for modulus of elasticity, but all other parameters were higher than for Red Delicious. All mechanical parameters for Red Delicious were low, showing its lesser strength against outside forces and stresses.

All the mechanical properties decreased from the first to second test series and all were significantly different except for modulus of elasticity. All parameters also showed a decrease between the first and last test series. Values for all mechanical properties in the first and last test series were significantly different from the other test series. It can be concluded from this that apples should not be stored for more than six months after harvest. Storage had the greatest effect on failure energy reduction and the least effect on modulus of elasticity reduction.

CONCLUSIONS

The effect of storage on the mechanical properties of apples was determined by performing uniaxial compression tests on Golden Delicious, Red Delicious, and Granny Smith apples using a Universal Testing Machine. It was seen that storage period has a significant effect on mechanical properties. Apples lose their strength over the period of storage, with the highest effect shown for failure energy and least effect for modulus of elasticity. Golden Delicious mechanical properties decreased more sharply than for the other cultivars over the first months of storage, especially during the last month of storage. Red Delicious and Granny Smith apples had the most uniform variations from the first to last months of storage.

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