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Mechanical Behaviour and Split Resistance of Chestnut under Compressive Loading

Yeşim Benal YURTLU[a], Elçin YEŞİLOĞLU[a]

[a] *Ondokuz Mayıs University, Faculty of Agriculture, Department of Agricultural Machinery, 55139, Kurupelit, Samsun, TURKEY*

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Corresponding author: Yeşim Benal YURTLU, e-mail: yurtlu@omu.edu.tr, Tel: +(362) 312 19 19/1256

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ABSTRACT

The mechanical properties of four varieties of chestnut (namely; Albayrak, Altınay, Ünal and 554-14) were determined in terms of average rupture force, deformation, rupture energy and firmness. Samples at various moisture contents were compressed by parallel plate along the X, Y and Z axes. Physical characteristics of the chestnut such as dimensions, geometric mean diameter, sphericity, volume and surface area were determined. The results showed that the rupture force, deformation and rupture energy values generally increase with increasing moisture content. The differences in firmness with moisture content are not statistically significant in the all orientations. The maximum rupture energy values at all moisture levels as well as all varieties were obtained for chestnut loaded along either the X or Y axes. The results of the experiments indicated that, the lowest rupture energy value to split the shell of nuts was required along the Z axis.

Keywords: Chestnut; Mechanical properties; Rupture force; Rupture energy; Firmness

Sıkıştırma Yükü Altında Kestanenin Mekanik Davranışı ve Kabuk Yırtılma Direnci

ESER BİLGİSİ

Araştırma Makalesi — Tarım Teknolojileri

Sorumlu Yazar: Yeşim Benal YURTLU, e-posta: yurtlu@omu.edu.tr, Tel: +(362) 312 19 19/1256

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ÖZET

Bu çalışmada, dört farklı kestane çeşidinin (Albayrak, Altınay, Ünal ve 554-14) ortalama kabuk yırtılma direnci, deformasyon, kabuk yırtılma enerjisi ve sertlik değerleri belirlenmiştir. Farklı nem içeriğine sahip deneme numuneleri X, Y ve Z eksenleri olmak üzere üç farklı eksende paralel plakalar arasında sıkıştırılmıştır. Çalışmada kestane çeşitlerine ait, temel boyutlar, geometrik ortalama çap, küresellik, hacim ve yüzey alanı gibi fiziksel özellikler de belirlenmiştir. Araştırma sonuçlarına göre, genel olarak nem içeriğinin artmasıyla kabuk yırtılma direnci, deformasyon ve kabuk yırtılma enerjisinde artış görülmektedir. Nem içeriğine bağlı olarak sertlik değişimi tüm çeşitler için tüm yükleme yönlerinde istatistiksel olarak önemsiz bulunmuştur. En yüksek kabuk yırtılma enerjisi değerleri tüm nem içeriklerinde ve tüm çeşitler için X veya Y eksenlerinde ortaya çıkmaktadır. Deneme sonuçları kestane kabuğunun yırtılması için en düşük enerji değerine Z ekseninde ihtiyaç duyulduğunu göstermiştir.

Anahtar sözcükler: Kestane; Mekanik özellikler; Kabuk yırtılma direnci; Kabuk yırtılma enerjisi; Sertlik

1. Introduction

Chestnut is one of the most popular nuts in the world. The most important species are *Castanea dentata*, *Castanea pumila* and *Castanea chrysophilla* in North America; *Castanea mollissima* and *Castanea crenata* in Asia; and *Castanea sativa* in Europe. The native area of *C. sativa* extends to the southern part of Europe, from the south of England and the Iberian Peninsula to the closeness of Caspian Sea and North of Morocco and Algeria (Conedera et al 2004). Chestnut is mainly produced in China, Korea, Turkey, Bolivia, Italy, Japan, Portugal and Spain. Global production of chestnut is around 1.3 million tons and in Turkey it is given 55,395 tonnes according to the FAO statistics (FAO 2008). The world production of *C. sativa* is around 190,000 tonnes year^{-1}, with Turkey being the main producer (52,000 tonnes year^{-1}) (Bounous et al 2002). In Turkey, it is mainly produced in Black Sea region, Marmara region and west Anatolia. Chestnut has rich nutritional composition and high food value. They contain carbonhydrates (starch and sucrose sugar), dietary staple, reasonable quantities of vitamin C and potassium and very low fat. Economical importance of the chestnut is not only coming from the fresh nut but various kinds of products are also important. The nuts have consumed directly as a roasted or boiled form or evaluated as value added products such as chestnut dessert, candied and flour. For commercial purposes, chestnuts are often classified by size, being the smallest fruits used in the industry and the biggest fruits are destined to the fresh fruit market. Both fresh and processes materials show increasing tendency in respect of export quality. Chestnut contains relatively high moisture and the freshly harvested chestnut has a texture more akin to a fruit than a nut (Biju Cletus 2008). They are covered with thorny husk. The shell and pellicle of the chestnut are not eaten and need to be removed, preferably by mechanical means. Chestnut kernels are subject to major quality loss during processing. A key factor in developing chestnut markets beyond fresh market and seasonal sales is the ability to shell or peel the chestnut. The shell-removing operation causes to damaged and broken kernels due to the mechanical forces applied to the nut during these operations. Types of damage depend on the variety and physical characteristics of the chestnut and kernel. For preventing and maintaining maximum quality during post-harvest treatments, it is very important to determine some physical and mechanical properties of chestnuts.

So far many studies have been conducted on physical and mechanical properties of hard shelled nuts and kernels as hazelnut, pistachio nut, apricot, pine nut, almond, walnut, macadamia nut and cashew nut by Oloso & Clarke (1993), Liu et al (1999), Borghei et al (2000), Aydın (2002), Gezer & Dikilitaş (2002), Aydın (2003), Güner et al (2003), Vursavuş & Özgüven (2004), Vursavuş & Özgüven (2005), Aktaş et al (2007), Arslan & Vursavuş (2008) and Galedar (2009). There are also a few studies on physico-mechanical properties of chestnut. Yıldız et al (2009) investigated some pysico-chemical properties of wild chestnut fruit. They reported some physical properties such as geometric mean diameter, sphericity, projected area, bulk density, fruit density, porosity, projected area, terminal velocity, fruit hardness, static and dynamic coefficient of friction at 54.8% moisture content level as 19.62 mm, 0.89, 5.70 cm^2, 585.8 kg m^{-3}, 1135.68 kg m^{-3}, 49.19%, 14.51 m s^{-1}, 54.35-77.05 N, 0.295-0.424 and 0.253-0.356, respectively. Guyer et al (2009) tested a commercial peeling system for its performance with 21 different cultivars and size of chestnuts grown in the USA. In addition, the effects of the preheating temperature of the chestnut on the efficiency and effectiveness of the peeler was investigated. They reported that there is a size effect on the performance of the peeling machine. Also, high temperature could increase the susceptibility of chestnut to being broken during processing. Oymak (2004) determined that the main physical and mechanical parameters of mechanically peeling and cleaning of chestnut fruit of Aydın province in Turkey. They found that average width and height of the fruit, surface area, roundness, sphericity and cutting energy (with a saw toothed rotating knife) as 35.06 mm, 21.62 mm, 3014.88 mm^2, 0.8689, 0.8025 and 0.394 W, respectively. Yılmaz (2007) determined in her study shell breaking resistance and breaking energy of Sarıaşlama, Ayıtabanı and Vakit type chestnuts grown in Turkey. Chestnut types were broken by pressing parallel plates in three moisture levels (30%, 20% and 15%) and in three different axes (X, Y, Z). The test showed that in all chestnut types, breaking energy increased with increasing of moisture level.

The objective of this study is to document the physical and mechanical properties of chestnuts, considering variety, moisture content and loading orientation. The average rupture force, deformation at rupture point, rupture energy and firmness of the chestnuts are examined under compression of parallel plates.

2. Material and Methods

Chestnuts (*Castanea sativa* Miller), variety Albayrak, Altınay, Ünal and 555-14 from Black Sea region, Sinop and Samsun province in Turkey were used in this study. They were harvested in the harvesting seasons October and November 2009. Samples were stored in perforated polyethylene bags in a cold storage in 2–4°C until used. The experiments were carried out as soon as possible after chestnut purchased. The chestnuts were cleaned manually to remove all foreign matter, immature, broken or spoilt nuts. The moisture contents of the chestnut were determined using the method used by Yurtlu et al (2010) and expressed in wet basis. Experiments were performed at three moisture content levels. Before the experiments, moisture content levels of the nuts were adjusted to 42.08±2 % , 47.21±2% and 50.57±2% w.b. by drying the samples at a temperature of 30°C in different periods.

To determine the average size, a sample of 100 chestnuts from each variety was randomly selected. The three main dimensions namely length (L), width (W) and thickness (T) of chestnuts were determined by using a digital calliper having an accuracy of 0.01 mm. The geometric mean diameter, sphericity and surface area were calculated according to Yurtlu et al (2010). The three main dimensions were used to calculate the volume of individual chestnut in this study. The volume of the chestnut (V) was calculated from the following equation (Mohsenin 1980):

$$V = \frac{\pi}{6}(LWT) \qquad (1)$$

The mechanical properties of chestnuts under compression load were measured by a Lloyd Instrument Universal Testing Machines (Lloyd Instrument LRX Plus, Lloyd Instruments Ltd, An AMATEK Company). The device has three main parts: moving head, driving unit and data acquisition system (load cell, note book and connections and NEXYGEN Plus software) (Figure 1). For the splitting measurement of chestnuts, the device was equipment with a load cell of 500 N and measurement accuracy of load cell was 0.5%. Load cell was fixed to moving head. The chestnut placed on the fixed plate considering the variation of moisture content and loading orientations and pressed by plate on moving head at the 10 mm min^{-1} speeds until rupture or splitting of shell occurred. Rupture point was detected from force-deformation curve, where there is a sudden drop in force. The mechanical properties of chestnut were expressed in terms of rupture force, deformation at rupture point, rupture energy and firmness. The three compression axes (X, Y, Z) for the chestnut were used to determine the rupture force, deformation, rupture energy and firmness (Figure 2). The X axis (force F_x) is the loading axis through the length dimension, while the Y axis (force F_Y) is

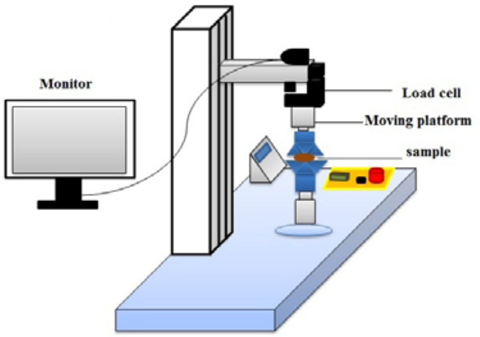

Figure 1-Lloyd Instrument universal testing machine
Şekil 1-Lloyd Instrument üniversal test cihazı

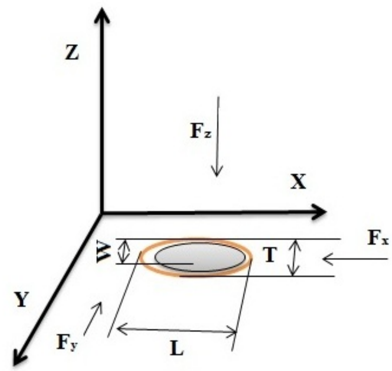

Figure 2-Representation of the three axes and three perpendicular dimensions of chestnut
Şekil 2-Kestaneye ait üç boyut ve yük uygulama eksenleri

the transverse axis containing the middle dimension (width) at right angles to the X axis, and Z axis (force F_z) is the transverse axis containing the minimum dimension (thickness).

The force-deformation curves were plotted for each test of chestnut. Mechanical properties at rupture were measured by using these curves. Absorbed energy by the sample was determined by calculating the area under the force-deformation curve done by utilization of computing software. The firmness values at rupture point were determined by using the following equation (Vursavuş & Özgüven 2005):

$$Q = \frac{F}{D_r} \tag{2}$$

where Q is the firmness in N mm^{-1}; F is the rupture force in N; D_r is the deformation at rupture point in mm.

In this study, 4×3×3 treatments were considered as four chestnut varieties, three moisture levels and three loading orientations. For each treatment, 20 samples were randomly selected and the average values of at least 10 experiments were reported. Data were statistically analysed using complete randomized block design to find the effect of variety, moisture content level and loading orientation on rupture force, deformation at rupture point, rupture energy and firmness of chestnut under applied load.

3. Results and Discussion

3.1. Physical properties

Table 1 shows the mean and standard error values of chestnut dimensions obtained from the measurements at moisture content of 50.57±2% w.b. for four different varieties. The length, width and thickness of chestnut varieties were found to be between 24.32 to 33.25, 24.53 to 27.78, 16.50 to 22.04 mm at 50.57±2% w.b., respectively. Geometric mean diameter, sphericity, volume and surface area of chestnut varieties were found to be between 21.39 to 26.36 mm, 0.79 to 0.87 %, 5093.45 to 9691.15 mm^3, and 1442.18 to 2190.99 mm^2 at same moisture level, respectively.

3.2. Rupture force

Table 2 summarized all measurement parameters and some statistical values of experiment. The force required to initiate chestnut shell splitting increased in all orientations as the moisture content increased. The reason of this trend can be attributed to the fact that at higher moistures, shell of chestnut was flexible and this was responsible for the initial raise in rupture force. When the chestnuts were dried, the shell

Table 1-Means and standard errors of physical properties of the chestnut varieties at moisture content of 50.57±2% w. b.

Çizelge 1-Kestane çeşitlerinin 50.57±% 2 y.b. nem değerinde fiziksel özelliklerine ait ortalama değerleri ve standart hataları

Properties	*Varieties*			
	Albayrak	*Altınay*	*Ünal*	*554-14*
Length, mm	30.10±0.26	32.77±0.26	24.32±0.25	33.25±0.20
Width, mm	27.36±0.22	25.89±0.21	24.53±0.14	27.78±0.15
Thickness, mm	17.55±0.21	22.04±0.23	16.50±0.19	19.89±0.24
Geometric mean diameter, mm	24.36±0.21	26.36±0.15	21.39±0.14	26.34±0.15
Sphericity, %	0.81± 0.01	0.82±0.01	0.87±0.01	0.79±0.26
Volume, mm^3	7695.44±198.56	9691.15±179.28	5093.45±102.16	9660.86±69.46
Surface area, mm^2	1872.81± 32.12	2190.99± 16.47	1442.18±18.44	2186.87±25.86

became eggshell and this resulted in a decrease in rupture force. The rupture force along the X axis was the greatest for Altınay and ranged from 337.90 to 482.49 N and followed by Albayrak (179.47-447.96 N), 554-14 (220.98-339.89 N) and Ünal (230.17-324.89 N). The rupture force along the Y axis was the same trends with X axis: Altınay (275.81- 520.90 N), Albayrak (100.23-491.35 N), 554-14 (161.03-424.00 N) and Ünal (197.58-376.40 N). The rupture force along the Z axis was the greatest for Albayrak and ranged from 273.86 to 719.12 N and followed by Altınay (319.82-565.87 N), 554-14 (179.26-505.20 N) and Ünal (321.56-416.39 N). The results show that generally the rupture force along the Z axis for all varieties and all moisture contents were always more than those along the other axes. The rupture force was the greatest at 50.57±2% w.b. moisture content level and followed by 47.21±2 % and 42.08±2% w.b. moisture content levels. Sharifian & Derafshi (2008) in walnut reported similar trends. Table 3 shows the equations representing relationship between moisture content and rupture force of chestnuts compressed along X, Y and Z axis. Statistical analysis showed that the effect of variety, moisture content, orientation of loading and variety by moisture content, variety by orientation of loading, moisture content by orientation of loading interactions on rupture force were significant (P<0.01).

3.3. Deformation

The equations representing the relationships between deformation and moisture contents along the X, Y and Z axes for each chestnut variety and their coefficient of determination (R^2) are given in Table 4. Deformations occurring at chestnut rupture generally increases as the moisture content increases. This is the same trends as rupture forces and related to the chestnut mechanical properties. The deformation value for chestnut compressed with along the X axis was for Albayrak (4.04-7.76 mm), and the lowest one was for 554-14 (2.98-6.27 mm). For other varieties, the deformation values were Altınay (3.35-6.34 mm), Ünal (3.65-6.11 mm). The deformation value along the Y axis was found to be greatest again for Albayrak (2.80-7.63 mm) followed by Ünal (3.26-7.24 mm), Altınay (2.96-7.00 mm) and 554-14 (2.80-6.87 mm). The corresponding value along the Z axis was the greatest for Albayrak (2.90-4.88 mm), followed by Ünal (2.57-4.34 mm), Altınay (2.34-4.06 mm) and finally the lowest for 554-14 (1.63-3.9 mm). The deformation values along the Z axis for all varieties and moisture content levels were less than those along the other axes. According to Duncan's multiple range test result, there is no significant difference between X and Y axis for the deformation at rupture point statistically. The deformation values was the greatest at 50.57±2 % w. b. moisture content level as rupture force, and decreased with decreasing the moisture contents. Statistical analysis showed a significant difference among the moisture content levels for the deformation (P<0.01).

Table 2-Measurement parameters and some statistical values

Çizelge 2-Ölçüm parametreleri ve bazı istatistik değerleri

Varieties	*Moisture content, %*	*Orientation of loading*	*Rupture force, N*	*Deformation, mm*	*Rupture energy, J*	*Firmness, N mm^{-1}*
Albayrak	42.08±2	X	179.47±18.14	4.04±1.03	0.33±0.04	46.54± 4.68
		Y	100.23±15.34	2.80±1.01	0.13±0.02	36.01± 3.17
		Z	273.86±41.85	3.09±0.85	0.29±0.05	85.93± 8.30
	47.21±2	X	291.89±36.85	4.53±1.13	0.57±0.09	64.52± 5.62
		Y	221.15±20.98	4.51±1.09	0.37±0.05	50.16± 3.67
		Z	342.11±35.65	2.90±0.86	0.37±0.05	121.54±10.32
	50.57±2	X	447.96±46.22	7.76±1.21	1.44±0.18	59.48± 6.41
		Y	491.35±27.36	7.63±1.01	1.45±0.13	64.73± 3.24
		Z	719.12±41.62	4.88±0.94	1.25±0.12	150.65±10.11
Altınay	42.08±2	X	337.90±41.78	3.35±1.46	0.63±0.15	119.97±11.81
		Y	275.81±33.08	2.96±0.89	0.40±0.06	92.06± 8.36
		Z	319.82±39.71	2.34±0.83	0.35±0.07	137.29± 9.26
	47.21±2	X	406.60±25.44	4.06±0.89	0.79±0.07	101.75± 6.35
		Y	317.25±45.14	3.88±1.06	0.59±0.09	85.22±11.39
		Z	460.15±24.66	3.52±1.12	0.72±0.09	145.08±14.90
	50.57±2	X	482.49±23.35	6.34±1.01	1.46±0.12	76.76± 2.82
		Y	520.91±32.32	7.00±1.19	1.55±0.16	74.92± 3.15
		Z	565.87±27.11	4.06±0.99	0.99±0.07	145.65±10.79
Ünal	42.08±2	X	230.17±22.02	3.88±1.25	0.40±0.05	67.65±10.02
		Y	197.98±19.98	3.81±1.06	0.36±0.05	52.70± 4.28
		Z	321.56±22.17	2.57±0.65	0.32±0.02	129.83±12.81
	47.21±2	X	259.41±22.78	3.65±0.81	0.38±0.04	70.81± 5.33
		Y	198.63±23.99	3.26±1.16	0.34±0.07	63.52± 3.90
		Z	327.35±17.19	3.34±0.76	0.37±0.02	100.25± 6.59
	50.57±2	X	324.89±17.16	6.11±0.97	0.81±0.06	53.29± 1.77
		Y	376.40±32.67	7.24±1.36	1.04±0.14	52.18± 2.97
		Z	416.39±29.92	4.34±0.73	0.67±0.05	97.13± 7.30
554-14	42.08±2	X	241.75±26.86	2.98±0.92	0.35±0.06	80.24± 4.08
		Y	183.09±33.20	2.80±1.02	0.26±0.08	64.25± 5.86
		Z	179.26±26.36	1.63±0.75	0.13±0.02	114.05±14.36
	47.21±2	X	220.98±23.92	3.30±0.86	0.33±0.05	66.57± 4.15
		Y	161.03±32.20	3.30±0.93	0.24±0.06	47.38± 6.45
		Z	182.03±32.23	1.97±0.87	0.16±0.04	89.23± 7.13
	50.57±2	X	339.89±22.74	6.27±1.01	1.03±0.11	54.15± 2.19
		Y	424.00±28.64	6.87±1.12	1.30±0.14	62.18± 3.45
		Z	505.20±36.38	3.90±0.90	0.85±0.13	129.02± 4.20
Means						
Albayrak			334.65±20.97^{b}	4.65±1.42^{c}	0.68±0.06^{b}	74.65± 4.26^{a}
Altınay			415.02±14.42^{c}	4.28±1.38^{b}	0.86±0.05^{c}	107.95± 4.10^{b}
Ünal			296.91±10.82^{a}	4.31±1.33^{b}	0.53±0.03^{a}	75.49± 3.3^{a}
554-14			278.85±16.05^{a}	3.69±1.38^{a}	0.53±0.05^{a}	80.34± 3.5^{a}
	42.08±2		234.84±10.2^{a}	3.06±1.1^{a}	0.33±0.05^{a}	84.43± 3.8^{a}
	47.21±2		286.43±11.3^{b}	3.52±1.0^{b}	0.44±0.06^{b}	85.01± 3.3^{a}
	50.57±2		467.58±12.4^{c}	6.02±1.3^{c}	1.16±0.11^{c}	84.99± 3.4^{a}
		X	312.28±11.2^{a}	4.68±1.3^{b}	0.71±0.08^{b}	71.58± 2.4^{b}
		Y	297.50±14.7^{a}	4.79±1.0^{b}	0.67±0.08^{b}	62.20± 2.0^{a}
		Z	388.30±16.2^{b}	3.24±1.3^{a}	0.55±0.06^{a}	120.83± 3.3^{c}
P values						
Variety			<0.001	<0.001	<0.001	<0.001
Moisture content			<0.001	<0.001	<0.001	0.852
Orientation of loading			<0.001	<0.001	<0.001	<0.001
Variety×Moisture Content			<0.001	0.055	<0.001	<0.001
Variety×Orientation.of loading			0.003	0.347	0.282	0.201
Moisture content×Ori.of loading			<0.001	<0.001	<0.001	<0.001
Var. × Mois.cont. × Ori.of loading			0.163	0.352	0.947	0.31

Table 3-Equations representing relationship between the rupture force along the X, Y and Z axis and moisture content for chestnuts

Çizelge 3-Kestane çeşitleri için X, Y ve Z eksenlerinde kabuk yırtılma direncinin neme bağlı değişimini veren eşitlikler

Variety	*Orientation of loading*	*Equation*	R^2	*P values*
Albayrak	X	$F_x=-948.3+28.44M_c$	0.99	<0.001
	Y	$F_Y=11887.796-581.451\mathrm{M}_c+7.138M_c^2$	0.95	<0.001
	Z	$F_z=20908-994.1\mathrm{M}_c+11.94M_c^2$	0.89	<0.001
	X	$F_x=-357.6+1641M_c$	0.99	0.003
Altınay	Y	$F_Y=18800-834.3\mathrm{M}_c+9.363M_c^2$	0.91	0.008
	Z	$F_z=-888.2+28.60M_c$	0.99	<0.001
	X	$F_x=-290.5+12.01\mathrm{M}_c$	0.97	0.004
Ünal	Y	$F_Y=13085.029-576.627M_c+6.435_c^2$	0.78	0.006
	Z	$F_z=205.8+12.01M_c$	0.80	0.013
	X	$F_x=8114-333.9M_c+3.526M_c^2$	0.90	0.029
554-14	Y	$F_Y=16104-679.1M_c+7.220M_c^2$	0.85	0.001
	Z	$F_z=17881.638-760.522M_c+8.149M_c^2$	0.76	<0.001

Table 4-Equations representing relationship between the deformation along the X, Y and Z axis and moisture content for chestnuts

Çizelge 4-Kestane çeşitleri için X, Y ve Z eksenlerinde deformasyonun neme bağlı değişimini veren eşitlikler

Variety	*Orientation of loading*	*Equation*	R^2	*P values*
	X	$D_{rx}=184.7-8.689M_c+0.1041M_c^2$	0.88	0.001
Albayrak	Y	$D_{ry}=125.9-6.132M_c+0.07631M_c^2$	0.99	0.003
	Z	$D_{rz}=3669-158.1M_c+1.704M_c^2$	0.85	<0.001
	X	$D_{rx}=198.3-8.819M_c+0.09948M_c^2$	0.91	0.016
Altınay	Y	$D_{ry}=273.2-12.22M_c+0.1377M_c^2$	0.96	<0.001
	Z	$D_{rz}=-6.397+0.2078M_c$	0.93	<0.001
	X	$D_{rx}=214.7-9.353M_c+0.1034M_c^2$	0.79	0.001
Ünal	Y	$D_{ry}=331.2-14.53M_c+0.1607M_c^2$	0.89	<0.001
	Z	$D_{rz}=-7.116+0.2255M_c$	0.98	<0.001
	X	$D_{rx}=205.2-8.605M_c+0.09139M_c^2$	0.85	<0.001
554-14	Y	$D_{ry}=258.7-10.87M_c+0.1152M_c^2$	0.89	<0.001
	Z	$D_{rz}=86.98-3.732M_c+0.04076M_c^2$	0.90	0.006

3.4. Rupture energy

It has been shown in Table 5 that the variation of rupture energies along the X, Y and Z axes for chestnuts as a function of moisture content and variety. Absorbed energy for chestnut shell split increased with increasing the moisture content levels. The rupture energy was the greatest at a moisture content of 50.57±2% w.b. and decreased with decreasing the moisture contents as rupture force. Similar trends were also observed by Yılmaz (2007) for chestnut varieties, Sharifian & Derafshi (2008) for walnut, Güner et al (1999) for apricot stone, Güner et al (2003) for hazelnut, Oloso & Clarke (1993) for cashew nut and Altuntaş & Yıldız (2007) for faba bean grain. The rupture energy along the X axis was the greatest for Altınay (0.63-1.46 J) followed by Albayrak (0.33-1.44 J), 554-14 (0.33-1.03 J) and Ünal (0.38-0.81 J). The rupture energy along the Y axis was the same trends with X axis: Altınay (0.40-

Table 5-Equations representing relationship between the rupture energy along the X, Y and Z axis and moisture content for chestnuts

Çizelge 5-Kestane çeşitleri için X, Y ve Z eksenlerinde kabuk yırtılma enerjisinin neme bağlı değişimini veren eşitlikler

Variety	*Orientation of loading*	*Equation*	R^2	*P values*
Albayrak	X	E_x=45.09-2.170M_c+0.02624M_c^2	0.97	0.003
	Y	E_Y=57.62-2.777M_c+0.03344M_c^2	0.99	<0.001
	Z	E_z=52.41-2.495M_c+0.02975M_c^2	0.86	<0.001
Altınay	X	E_x=59.77-2.669M_c+0.03001M_c^2	0.93	0.009
	Y	E_Y=88.00-3.944M_c+0.04426M_c^2	0.94	0.001
	Z	E_z=-2.784+0.07433M_c	0.95	<0.001
Ünal	X	E_x=32.10-1.415M_c+0.01574M_c^2	0.80	0.001
	Y	E_Y=53.77-2.383M_c+0.02651M_c^2	0.80	0.003
	Z	E_z=-1.667+0.04545M_c	0.93	<0.001
554-14	X	E_x= 32.96-1.414M_c+0.01529M_c^2	0.80	0.009
	Y	E_Y=59.76-2.552M_c+0.02729M_c^2	0.79	<0.001
	Z	E_Y=36.73-1.577M_c+0.01695M_c^2	0.81	0.005

1.55 J), Albayrak (0.13-1.45 J), 554-14 (0.24-1.30 J) and Ünal (0.34-1.04 J). The maximum rupture energy along the Z axis was obtained for Altınay (0.35-0.99 J) followed by Albayrak (0.29-1.25 J), Ünal (0.32-0.67 J) and 554-14 (0.13-0.85 J). Statistical analysis showed that the effect of variety, moisture content, orientation of loading and variety by moisture content, moisture content by orientation of loading interactions on the rupture energy was found to be statistically significant (P<0.01). The results showed that compression along the Z axis required less energy for rupture than other axes. The rupture energy difference between X and Y axis was not statistically significant according to Duncan's multiple range tests.

3.5. Firmness

The equations representing relationship among the values along the X, Y and Z axes of chestnut and moisture content for each chestnut variety are presented in Table 6. In the case of firmness along the X axis, the highest value was obtained for Altınay (76.76-119.97 N mm^{-1}) followed by 554-14 (54.15-80.24 N mm^{-1}), Ünal (53.29-70.81 N mm^{-1}) and Albayrak (46.54-64.52 N mm^{-1}). The maximum firmness along the Y axis was determined for Altınay (74.92-92.06 N mm^{-1}) followed by 554-14 (47.38-64.25 N mm^{-1}), Ünal (52.18-63.52 N mm^{-1}) and Albayrak (36.01-64.73 N mm^{-1}). The corresponding value along the Z axis was the greatest for Altınay (137.28-145.65 N mm^{-1}). Other varieties were ranked as Albayrak (85.93-150.65 N mm^{-1}), 554-14 (89.23-129.02 N mm^{-1}) and Ünal (97.13-129.83 N mm^{-1}). Statistical analysis showed that the effect of variety, orientation of loading and variety by moisture content, moisture content by orientation of loading interaction on firmness was found to be statistically significant (P<0.01). The differences in firmness with moisture content are not statistically significant. Firmness values are highest in Z axis and the firmness difference between the X and Y axis was not statistically significant according to Duncan's multiple range tests.

4. Conclusions

This study indicated that chestnut required the lowest rupture energy to split chestnut shell compressed along the Z axis as compared with other two axes. Results show that the rupture energy was the highest for Altınay 1.55 J along the Y axis, and lowest for 554-14 variety 0.13 J along the Z axis. It can be concluded that compression along the Z axis is more suitable than the other axis since splitting of the chestnut shell is expected to be done with minimum energy. According to results of the analysis, the effect of moisture content on rupture force, deformation and rupture energy was found to be statistically significant (P<0.01) while there was statistically no significant effect of moisture content on firmness. The rupture force value was decreased from 467.58 to 234.84 N as moisture content increased from 42.08±2 to 50.57±2%. It can be remarked that before removing of the shell, the chestnut should be dried to suitable moisture content regarding to purpose of using. A linear and non-linear relationship with good degrees of fit between the moisture content and mechanical properties was obtained for all orientation of loading.

Table 6-Equations representing relationship between the firmness along the X, Y and Z axis and moisture content for chestnuts

Çizelge 6-Kestane çeşitleri için X, Y ve Z eksenlerinde sertliğin neme bağlı değişimini veren eşitlikler

Variety	*Orientation of loading*	*Equation*	R^2	*P values*
Albayrak	X	Q_x=-19.90+1.733M_c	0.92	0.048
	Y	Q_x =-88.33+3.139M_c	0.99	<0.001
	Z	Q_x=-421.5+11.95M_c	0.98	<0.001
Altınay	X	Q_x=-325.1-4.831M_c	0.97	0.001
	Y	Q_x =177.7-1.988M_c	0.98	0.018
	Z	Q_x=2977-124.9M_c-1.365M_c^2	0.80	0.012
Ünal	X	Q_x=303.6-4.165M_c	0.87	0.016
	Y	Q_x=-1508+67.59M_c-0.7265M_c^2	0.79	0.022
	Z	Q_x=-1433+66.44M_c-0.7328M_c^2	0.83	0.043
554-14	X	Q_x=209.2-2.906M_c	0.99	<0.001
	Y	Q_x =2291-91.77M_c+0.9369M_c^2	0.83	<0.001
	Z	Q_x=3861-156.0M_c-1.612M_c^2	0.96	0.008

Nomenclature

D	geometric mean diameter, mm
D_r	deformation at rupture point, mm
E	rupture energy, J
F	rupture force, N
L	length, mm
T	thickness, mm
W	width, mm
Q	firmness, N mm^{-1}
S	surface area, mm^2
$Ø$	sphericity, %
M_c	moisture content, % w.b.
V	volume of chestnut, mm^3

References

Aktaş T, Polat R & Atay U (2007). Comparison of mechanical properties of some selected almond cultivars with hard and soft shell under compression loading. *Journal of Food Process Engineering* **30**:773-789

Altuntaş E & Yıldız M (2007). Effect of moisture content on some physical and mechanical properties of faba bean (*Vicia faba* L.) grains. *Journal of Food Engineering* **78**:174-183

Arslan S & Vursavuş K K (2008). Physico-mechanical properties of almond nut and its kernel as a function of variety and moisture content. *The Philippine Agricultural Scientist* **91**(2):171-179

Aydın C (2002). Physical properties of hazelnuts. *Biosystems Engineering* **82**:297-303

Aydın C (2003). Physical properties of almond nut and kernel. *Journal of Food Engineering* **60**:315-320

Biju Cletus A & Carson J K (2008). Drying curves and apparent diffusivity of New Zealand chestnut variety 210152. *Journal of Food Engineering* **85**:381-386

Borghei A M, Khazaei J & Tavakoli T (2000). Design, construction and testing of walnut cracker. International Conference on Agricultural Engineering, University of Wawick, UK., July 2-7, Paper no: 00-PH-029

Bounous G, Barrel A, Beccaro G, Lovisolo C & Gomes J A (2002). Inventory of Chestnut Research, Germplasm and References, FAO Regional Office for Europe, Rome, Italy

Conedera M, Krebs P, Tinner W, Pradella M & Torriani D (2004). The cultivation of *Castanea sativa* (Mill.) in Europe, from its origin to its diffusion on a continental scale. *Vegetation History and Archaeobotany* **13**:161-179

FAO (2008). Food and Agriculture Organization of the United Nations Agricultural Statistics. Available: http://www.fao.org

Galedar M N, Mohtasebi S S, Tabatabaeefar A, Jafari A & Fadaei H (2009). Mechanical behavior of pistachio nut and its kernel under compression loading. *Journal of Food Engineering* **95**:499-504

Gezer I & Dikilitaş S (2002). The study of work process and determination of some working parameters in an apricot pit processing plant in Turkey. *Journal of Food Engineering* **53:**111-114

Guyer D, Mandujano M & Fulbright D W (2009). Influence of Selected Factors on Efficiency and Effectiveness of a Peeling Machine for Chestnuts. Castanea 2009, 1 st European Congress on Chestnut Abstarcats Book, Cuneo, Italy

Güner M, Vatandaş M & Dursun E (1999). Determination of cracking characteristics of some varieties of apricot stones. *Journal of Agricultural Sciences* **5**(1):95-103

Güner M, Dursun E & Dursun İ G (2003). Mechanical behaviour of hazelnut under compression loading. *Biosystems Engineering* **85**(4):485-491

Liu R, Wang C H & Bathgate R G (1999). Fracture analysis of cracked macadamia nutshell under contact load between two rigid plates. *Journal of Agricultural Engineering Research* **74**:243-250

Mohsenin N N (1980). Physical Properties of Plant and Animal Material. Gordon and Breach Science Publishers Inc., New York, USA

Oloso A O & Clarke B (1993). Some aspects of strength properties of cashew nuts. *Journal of Agricultural Engineering Research* **55**:27-43

Oymak Z (2004). A study on determining the physical and mechanical properties for the purpose of mechanically peeling chestnut fruit's shell and seed coat. Adnan Menderes University, Master Thesis (Unpublished), Aydın, Turkey

Sharifian F & Derafshi M H (2008). Mechanical behavior of walnut under cracking conditions. *Journal of Applied Sciences* **8**:886-890

Vursavuş K & Özgüven F (2004). Mechanical behaviour of apricot pit under compression loading. *Journal of Food Engineering* **65**:261-265

Vursavuş K & Özgüven F (2005). Fracture resistance of pine nut to compressive loading. *Biosystem Engineering* **90**(2):185-191

Yıldız M U, Özcan M M, Çalışır S, Demir F& Er F (2009). Physico-chemical properties of wild chestnut (*Castanea sativa* Mill.) fruit grown in Turkey. *World Applied Sciences Journal* **6**(3):365-372

Yılmaz B (2007). Determination of mechanical behavior of chestnuts (Castanea) under compression loading. Ankara University, Master Thesis (Unpublished), Ankara, Turkey

Yurtlu Y B, Yeşiloğlu E & Arslanoğlu F (2010). Physical properties of bay laurel seeds. *International Agrophysics* **24**:325-328