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Mechanical Behaviour of Hazelnut under Compression Loading

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Aci Findik, *Cakildak*, *Tombul*, and *Güney Karasi* varieties of hazelnut were loaded between two parallel plates to determine the specific deformation, rupture force, and rupture energy required to initiate shell and kernel rupture. The tests were carried out at two deformation rates of 0·52, and 0·91 mm s^{-1}, four moisture contents of 6, 11, 15, and 18% w.b., and three axes (X,Y,Z). The X-axis is the longitudinal axis through the hilum, while the Y-axis is the transverse axis containing the major dimension at right angles to the longitudinal axis, and the Z-axis is the transverse axis containing the minimum dimension. Physical characteristics of nut and kernel such as mass, dimensions, geometric mean diameter and sphericity were determined. Specific deformation and rupture energy of the shell generally increased in magnitude with an increase in moisture content while rupture force decreased for compression along the X- and Y-axis. The highest nut shell specific deformation, rupture force and rupture energy among the four varieties were obtained for *Aci Findik* nuts loaded along the Z-axis at a deformation rate of 0·52 mm s^{-1}. The *Tombul* and *Güney Karasi* varieties had the highest kernel rupture force and rupture energy, respectively.
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1. Introduction

Hazelnut (*Corylus avellana L.*) is a fruit consisting of a hard shell with a kernel inside it that can be eaten. Hazelnut is widely grown in different regions of Turkey. It is important for Turkey because of its export potential. Turkey is the biggest hazelnut producer with an average annual production of about 550 000 t between 1995 and 2000 (which is 72·7% of the world hazelnut production) and exports 75% of its hazelnut production with a value of one billion US dollars. There are about 283 million hazelnut trees which are cultivated in 536 963 ha (SSI, 2000; Ozdemir, 1999). The traditional harvesting methods are generally used whereby the limbs are shaken with a stick, by hand or by shoving, enabling the hazelnuts to be collected from the ground. Hazelnuts are subject to major quality loss during harvesting, threshing and processing. The most critical and delicate operation is nut shell cracking to extract the fragile whole kernel from the shell. The shelling operation leads to damaged and broken kernels due to the mechanical forces applied to the nut during the shelling operation. Damaging the kernels during the shelling process greatly reduces the market value of hazelnuts. The extent and types of damage depend on the characteristics of the hazelnut variety and of the sheller. One of the most important factors for shelling is the mechanical force applied to the hazelnut (Ozdemir, 1999). It is, therefore, important to study the mechanical behaviour of hazelnut for harvesting, conveying, storage, and shelling operation.

Liang (1977) developed a new processing system for maximising macadamia nut kernel recovery and found that the physical quality of the extracted kernels was influenced by the nut moisture content before cracking. According to Sarig *et al.* (1980) and Liang *et al.* (1984), nut and kernel deformations are influenced by moisture content for macadamia nut. Sahin *et al.* (1990) determined the physical and chemical characteristics of hazelnut grown and traded in the Middle and East Black Sea Coast of Turkey. Oloso and Clarke (1993) carried out quasi-static compression tests on roasted cashew nuts to investigate the effect of moisture content, pre-damage type, and direction of loading on rupture force, rupture energy, and rupture deformation. Rupture deformation and rupture energy increased

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Notation

D_p	geometric mean diameter, mm	W	minor axis dimension, mm
F_x, F_y,		X	longitudinal axis through the hilum
F_z	axial force, N	Y	transverse axis containing the minor dimension at right angles to the longitudinal axis
L	major axis dimension, mm		
L_u	undeformed nut dimension on the direction of the compression axis, mm	Z	transverse axis containing the minimum dimension (thickness)
L_f	deformed nut dimension on the direction of the compression axis, mm	ε	specific deformation, %
		Φ	sphericity, %
T	thickness, mm		

while rupture force decreased with increases in moisture content.

Beyhan (1996) measured the detachment force of hazelnut and investigated the possibility of mechanical harvesting with an eccentric type limb shaker. Ozdemir and Ozilgen (1997) compared the quality of hazelnuts in a commercial processing plant by determining the percentages of nuts that were damaged, broken, left in the shell, cracked, unbroken, recyclable, or undamaged. Liu *et al.* (1999) investigated the fracture behaviour of macadamia nut shell theoretically and numerically and found that the vertical cracking was beneficial to cracking the nut shell while the horizontal cracking was unhelpful unless it was long enough. Ozdemir (1999) compared the quality of hazelnuts shelled with modified conical sheller and stone sheller. The importance of the application of compressive force while shelling was emphasised. Braga *et al.* (1999) investigated force, specific deformation, and energy required for the initial rupturing of macadamia nut shell under compression as a function of moisture content, nut size, and compression load position. The experiments showed that there is a compression position for which force, specific deformation and energy values are minimal, independent of nut size and shell moisture. Navarrete and Chiralt (1999) reported that moisture content affected the mechanical properties of hazelnut. Aydin (2002) evaluated several physical properties of hazelnut and kernels as a function of moisture content and found that rupture force of nut and kernel decreased with increasing moisture content.

The objectives of this study were to determine the effects of moisture content, loading axis, and hazelnut variety on specific deformation, rupture force, and rupture energy required to achieve the initial rupture under compression.

2. Materials and methods

Aci findik (AF), *Cakildak* (Ç), *Tombul* (TO), and *Güney Karasi* (GK) varieties of hazelnut were used in this study. The hazelnuts used in these tests were supplied from Samsun province in 2000. They were cleaned to remove all foreign matter, and damaged and broken nuts. A screen was used to sort the remaining hazelnuts with sound shells according to size. The specific deformation, rupture force, and rupture energy of hazelnut varieties were determined.

The moisture content of the hazelnut was determined using the method recommended by Braga *et al.* (1999) and expressed in wet basis. In the tests, the moisture contents of 6, 11, 15 and 18% w.b. and three compression axes were used. Due to the fact that the *Tombul* variety was widely grown in Turkey, the effects of moisture content and loading axis on the mechanical behaviour of hazelnuts were investigated by using only the *Tombul* variety. With each of the four moisture levels and three loading axes, compression tests were performed at a deformation rate of $0{\cdot}52\,\mathrm{mm\,s^{-1}}$ for the *Tombul* variety to investigate the effects of shell moisture content on specific deformation, rupture force, and rupture energy.

In order to examine the effect of nut variety on specific deformation, rupture force, and rupture energy, the tests were carried out at a moisture content of 6% w.b., a deformation rate of $0{\cdot}52\,\mathrm{mm\,s^{-1}}$, and compression along the Z-axis for shell and at a moisture content of 6% w.b., a deformation rate of $0{\cdot}91\,\mathrm{mm\,s^{-1}}$, and compression along the X-axis for kernel.

To determine the average size of the hazelnut, a sample of 100 hazelnuts was randomly selected. The dimensions and mass of each nut used were determined. Along the three major perpendicular axes, the dimensions of the hazelnut were measured with a micrometer, which had an accuracy of 0·01 mm. The geometric mean diameter and the sphericity of the hazelnut were calculated by using the following relationships (Mohsenin, 1970):

$$D_p = (LWT)^{1/3} \tag{1}$$

$$\Phi = \frac{(LWT)^{1/3}}{L} 100 \tag{2}$$

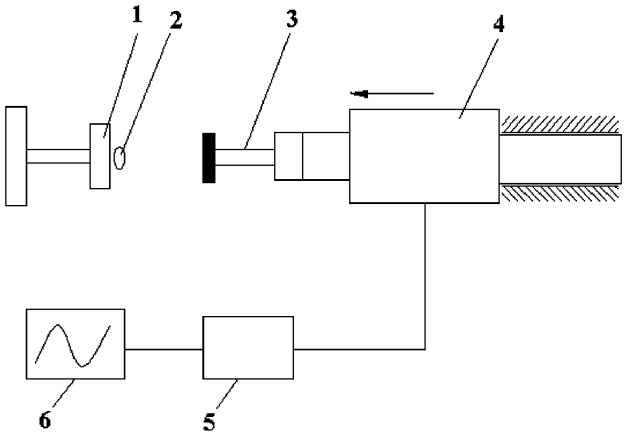

Fig. 1. Biological material test device: (1) fixed baseplate; (2) sample; (3) moving parallel plate; (4) dynamometer; (5) amplifier; (6) X–Y plotter

where: D_p is the geometric mean diameter in mm; Φ is the sphericity in %; L is the major axis dimension in mm; W is the minor axis dimension in mm; and T is the thickness in mm.

To obtain the mass, each sample was weighed by a balance reading to 0·001 g and to determine the mechanical behaviour of the hazelnut, a test device was developed for biological material. This device has three main components which are a fixed baseplate and a moving parallel plate, a driving unit, and the data acquisition system composed of a dynamometer of accuracy 0·1%, amplifier and XY plotter (*Fig. 1*). The hazelnut was placed on the baseplate and pressed by the moving parallel plate until the shell ruptured. Force–deformation curves were recorded.

The mechanical behaviour of hazelnut was expressed in terms of rupture force, rupture energy, and specific deformation required for initial rupture. Three replicates were made for each test and ten samples in each test were used. A typical force–deformation curve for compressed hazelnut is shown in *Fig. 2*. The values of the rupture force, rupture energy, and specific deformation for the initial rupture of shell and kernel were obtained from each compression curve. The rupture energy was determined directly from the chart by measuring the area under the force–deformation curve using a digital planimeter of an accuracy of $\pm$0·2% (model: Placom-Koizumi KP-80N).

The specific deformation was obtained from the following expression (Braga *et al.*, 1999):

$$\varepsilon = \frac{L_u - L_f}{L_u} 100 \qquad (3)$$

where: ε is the specific deformation in %; L_u is the undeformed nut dimension on the direction of the compression axis in mm; and L_f is the deformed nut dimension on the direction of the compression axis in mm.

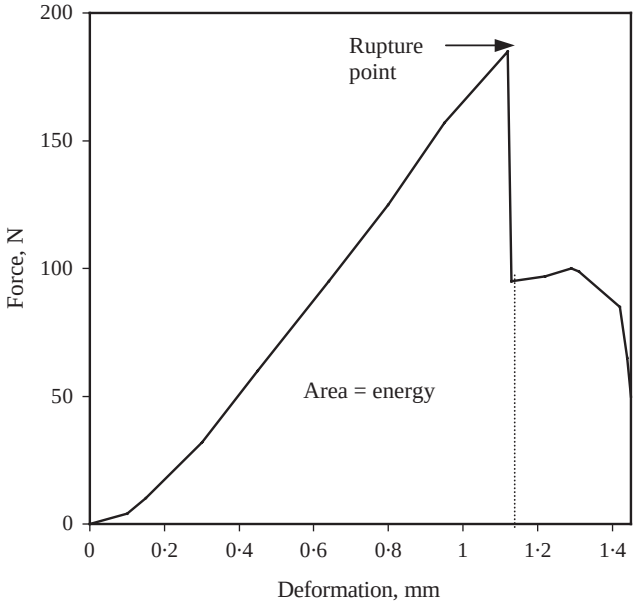

Fig. 2. Typical force–deformation curve for compressed hazelnut

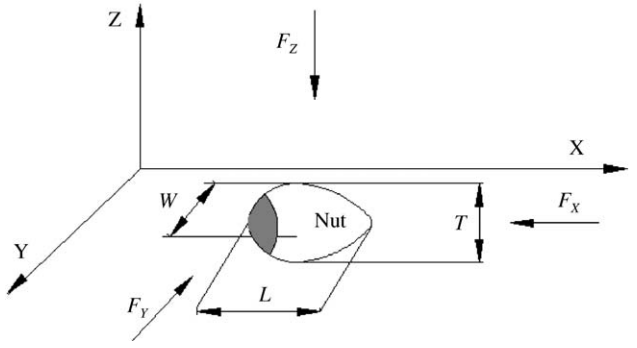

Fig. 3. Representation of the three axes and three perpendicular dimensions of nuts and kernels: X-axis, the longitudinal axis through the hilum containing the major dimension (length, L); Y-axis, the transverse axis containing the minor dimension (width, W) at right angles to the longitudinal axis; and Z-axis, the transverse axis containing the minimum dimension (thickness, T); F_x, F_y, and F_z, axial forces

The three compression axes (X, Y, Z) for the nut and kernel were used to determine the specific deformation, rupture force, and rupture energy (*Fig. 3*). The X-axis (force F_x) is the longitudinal axis through the hilum (length), while the Y-axis (force F_y) is the transverse axis containing the minor dimension (width) at right angles to the longitudinal axis, and the Z-axis (force F_z) is the transverse axis containing the minimum dimension (thickness).

Table 1
Nut and kernel dimensions and masses of hazelnut varieties

Variety	*Major dimension (length), mm*	*Minor dimension (width), mm*	*Minimum dimension (thickness), mm*	*Geometric mean diameter, mm*	*Sphericity, %*	*Mass, g*
Nut						
Aci Findik	19·76a	16·53b	14·46c	16·78b	84·91b	1·91b
Cakildak	19·26a	15·86b	14·76bc	16·52b	85·77b	1·34c
Tombul	18·58b	17·17b	15·73b	17·12b	92·14a	1·98b
Güney Karasi	19·63a	19·26a	16·92a	18·56a	94·56a	2·41a
Kernel						
Aci Findik	14·77b	13·09b	10·20b	12·54b	84·90b	0·92b
Cakildak	14·82b	11·88c	10·23b	12·20b	82·09b	0·79b
Tombul	15·69a	13·26bc	12·40a	13·72a	87·41ab	1·17a
Güney Karasi	15·44a	14·39a	12·80a	14·17a	91·76a	1·26a

Values in the same column followed by the same letter are not significantly different (probability $P < 0{\cdot}01$).

3. Results and discussion

Table 1 shows the average nut and kernel dimensions and masses of the hazelnut varieties used in the tests at the 6% w.b. The nut sizes of *Aci Findik*, *Cakildak*, *Tombul*, and *Güney Karasi* vary within the dimensions ranges of 14·46–19·76, 14·76–19·26, 15·73–18·58 and 16·92–19·63 mm, respectively. The kernel sizes of *Aci Findik*, *Cakildak*, *Tombul*, and *Güney Karasi* vary within the dimensions ranges of 10·20–14·77, 10·23–14·82, 12·40–15·69 and 12·80–15·44 mm, respectively. The *Güney Karasi* variety has the maximum geometric mean diameter and sphericity among the four varieties for nut and kernel. Dimensions and masses given in Table 1 were similar to the results reported by Sahin *et al*. (1990) and Aydin (2002).

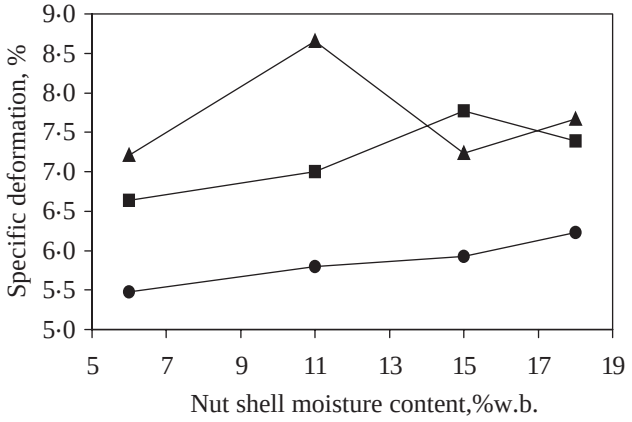

Fig. 4. Effect of nut shell moisture content and compression axis on specific deformation for a deformation rate of 0·52 mm s^{-1}: -●-, X-axis; -■-, Y-axis; -▲-, Z-axis

3.1. *Effects of shell moisture content and compression axis*

The specific deformation, rupture force, and rupture energy for the initial rupture of the nut as a function of nut shell moisture content and compression axis are presented in *Figs 4*, *5* and *6*, respectively. Specific deformation of the shell rupture generally increased as moisture content increased for compression along the X- and Y-axis except for moisture contents from 15–18% w.b. with compression along the Y-axis. Data for specific deformation related to the Z-axis did not show any dependence on moisture content (*Fig. 4*). The specific deformations along the X-axis for all moisture contents were always smaller than those along the other two axes. The maximum specific deformation (8·65%) was obtained at a moisture content of 11% w.b. for compression along the Z-axis, while the lowest (5·48%)

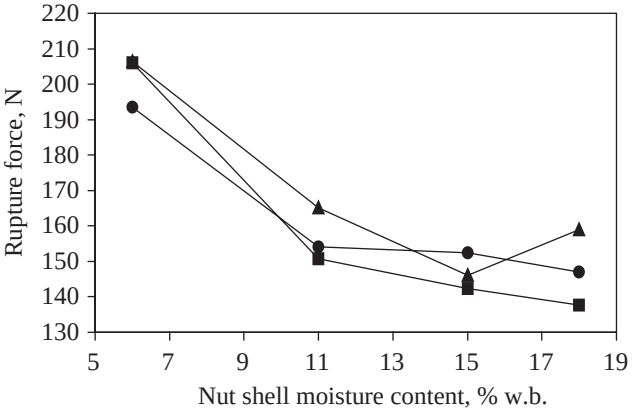

Fig. 5. Effect of nut shell moisture content and compression axis on rupture force for a deformation rate of 0·52 mm s^{-1}: -●-, X-axis; -■-, Y-axis; -▲-, Z-axis

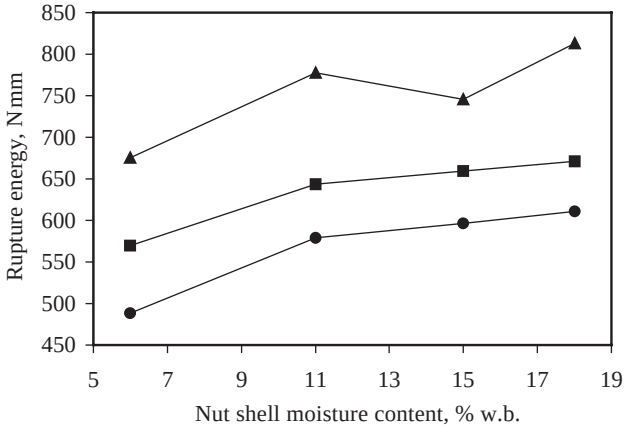

Fig. 6. Effect of nut shell moisture content and compression axis on rupture energy for a deformation rate of 0·52 mm s^{-1}: -●-, X-axis; -■-, Y-axis; -▲-, Z-axis

was at a moisture content of 6% w.b. for compression along the X-axis. Oloso and Clarke (1993) reported that deformation increased as moisture content increased for cashew nuts.

Fig. 5 shows the effects of moisture content and loading axis on the rupture force. It can be seen that there is a dependence on the nut shell moisture content. Rupture force decreases as moisture content increases for all three axes except from 15 to 18% moisture content for loading along the Z-axis. This indicates that greater forces were necessary to rupture the nuts with lower moisture content. The low rupture forces at higher moisture contents might have resulted from the fact that the nut tended to be very soft at high moisture content. As presented in *Fig. 5*, there did not appear to be any significant difference among the three axes but the effect of nut shell moisture content on the rupture force was significant (probability $P<0{\cdot}01$). Previous works have shown that rupture force decreased with increase in moisture content (Braga *et al*., 1999; Guner *et al*., 1999; Gezer *et al*., 2002; Aydin, 2002).

As presented in *Fig. 6*, in all cases rupture energy generally increased as moisture content increased except for moisture contents from 11 to 15% w.b. for loading along the Z-axis. The results are similar to those reported by Oloso and Clarke (1993) and Guner *et al*. (1999). The highest rupture energy (812·90 N mm) was obtained at a moisture content of 18% w.b. for loading along the Z-axis while the lowest (488·60 N mm) was at a moisture content of 6% w.b. for loading along the X-axis. Compression along the Z-axis required more energy for rupture than along the other two axes. Statistical analysis showed a significant difference between the forces along the X-, Y-, and Z-axis. At the lower moisture levels, the rupture energy was low and vice versa.

From these experiments, it was observed that all the parameters used to indicate hazelnut mechanical behaviour were dependent on the shell moisture content for compression along the X- and Y-axis, while no dependence was found for compression along the Z-axis. In terms of specific deformation, rupture force, and rupture energy required to initiate rupture shell, the hazelnuts have a higher strength when compressed along the Z-axis. Compression of hazelnuts at the hilum (X-axis) generally presents the least resistance to shell rupture. Therefore, in designing cracking machines the axes should be taken into consideration.

3.2. *Effects of hazelnut variety*

The specific deformation, rupture force, and rupture energy for the initial rupture of shell and kernel of nut varieties are presented in *Figs 7*, *8*, and *9*, respectively.

As can be seen in *Fig. 7*, the highest nut shell specific deformation was obtained for *Aci Findik* while the lowest was for the *Tombul* variety. The nut shell specific deformations of *Aci Findik*, *Cakildak*, *Tombul*, and *Guney Karasi* were 8·00, 6·44, 6·32, and 6·42%, respectively. There was no significant difference among the shell specific deformations of *Cakildak*, *Tombul*, and *Güney Karasi*. The kernel of the *Tombul* variety had the highest specific deformation while the kernel of the *Cakildak* variety had the lowest. The kernel specific deformations of *Aci Findik*, *Cakildak*, *Tombul*, and *Güney Karasi* were 6·85, 3·75, 9·35, and 7·06%, respectively. Statistical analysis showed that the kernel specific deformation differences among the four varieties were significant ($P<0{\cdot}01$).

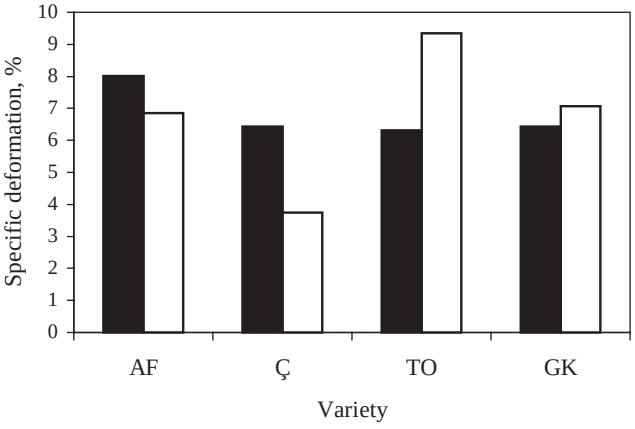

Fig. 7. Effect of nut variety on specific deformation for a moisture content of 6% w.b.: ■, shell, deformation rate of 0·52 mm s^{-1} along the Z-axis; □, kernel, deformation rate of 0·91 mm s^{-1} along the X-axis; AF, Aci findik; Ç, Cakildak; TO, Tombul; GK, Güney Karasi

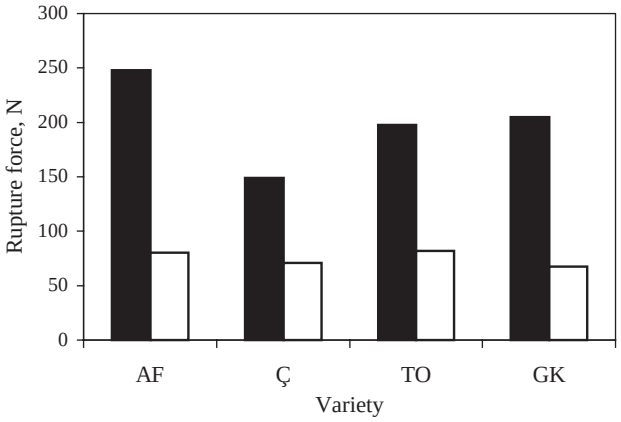

Fig. 8. Effect of nut variety on rupture force for 6% w.b.: ■, shell, deformation rate of 0·52 mm s^{-1} along the Z-axis; □, kernel, deformation rate of 0·91 mm s^{-1} along the X-axis; AF, Aci fındik; Ç, Cakildak; TO, Tombul; GK, Güney Karasi

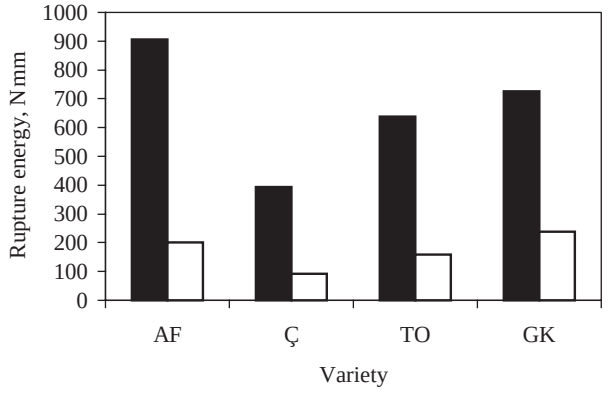

Fig. 9. Effect of nut variety on rupture energy for 6% w.b.: ■, shell, deformation rate of 0·52 mm s^{-1} along the Z-axis; □, kernel, deformation rate of 0·91 mm s^{-1} along the X-axis; AF, Aci fındik; Ç, Cakildak; TO, Tombul; GK, Güney Karasi

Values of rupture force of nut variety is shown in *Fig. 8*. As in the specific deformation, the highest nut shell rupture force was obtained for *Aci Findik* and minimum nut shell rupture force was obtained for *Cakildak*. The nut shell rupture forces of *Aci Findik*, *Cakildak*, *Tombul*, and *Guney Karasi* varieties are 247·74, 148·75, 197·45, and 204·73 N, respectively. Statistical analysis showed that the nut shell rupture force differences among the four varieties were significant ($P<0·01$). As in the specific deformation, the highest kernel rupture force was also obtained for *Tombul*. The kernel of *Güney Karasi* had the lowest rupture force. The kernel rupture forces of *Aci Findik*, *Cakildak*, *Tombul*, and *Güney Karasi* were determined as 80·19, 71·02, 81·73, and 67·80 N, respectively. The kernel rupture force differences among the four varieties were not significant.

Aci Findik required more nut shell rupture energy than other three varieties as shown in *Fig. 9*. *Cakildak* had the smaller energy to rupture the nut shell. Statistical analysis showed that the nut shell rupture energy differences among the four varieties were significant ($P<0·01$). The nut shell rupture energies of *Aci Findik*, *Cakildak*, *Tombul*, and *Güney Karasi* are 905·39, 393·86, 637·27, and 726·33 N mm, respectively. The highest energy required to initiate kernel rupture was obtained for *Güney Karasi*. The minimum kernel rupture energy was obtained for *Cakildak*. Statistical analysis showed that the kernel rupture energy differences among the nut varieties were significant ($P<0·01$). The kernel rupture energies of *Aci Findik*, *Cakildak*, *Tombul*, and *Güney Karasi* were 201·69, 92·45, 158·63, and 239·01 N mm, respectively.

4. Conclusions

The results of this research can be summarised as follows.

(1) The values of geometric mean diameter of the nuts of the *Aci Findik*, *Cakildak*, *Tombul*, and *Güney Karasi* varieties were 16·78, 16·52, 17·12 and 18·56 mm, respectively. The values of geometric mean diameter of the kernels of *Aci Findik*, *Cakildak*, *Tombul*, and *Güney Karasi* varieties were 12·54, 12·20, 13·72 and 14·17 mm, respectively. The mass of nut and kernel varied from 1·34 to 2·41 g and from 0·79 to 1·26 g, respectively.

(2) The parameters used to indicate hazelnut mechanical behaviour were dependent on the shell moisture content for compression along the X- and Y-axis, while no dependence was found for compression along the Z-axis. Specific deformation and rupture energy of the nut shell generally increased with moisture content while rupture force decreased for compression along the X- and Y-axis, at a deformation rate of 0·52 mm s^{-1} for the *Tombul* variety. The highest shell specific deformation, rupture force, and rupture energy were obtained for compression along the Z-axis at a deformation rate of 0·52 mm s^{-1} for the *Tombul* variety. The nut shell moisture content had significant effects on the rupture force and energy (probability $P<0·01$), respectively.

(3) For nuts maintained at a moisture content of 6% w.b. subjected to deformation rate of 0·52 mm s^{-1} and compressed along the Z-axis, the highest nut shell specific deformation, rupture force, and rupture energy were obtained for *Aci Fındik* variety among the four nut varieties. The *Cakildak* variety

required the lowest nut shell rupture force and rupture energy. The values of nut shell specific deformation, rupture force and rupture energy for *Tombul* and *Güney Karasi* were close to each other. The results showed that the nut shell rupture force and rupture energy differences between the four nut varieties were significant ($P < 0{\cdot}01$).

(4) The kernel of the *Tombul* variety had the highest specific deformation while the kernel of the *Cakildak* variety had the lowest. The highest kernel rupture force and rupture energy were obtained for the *Tombul* variety and *Güney Karasi*, respectively. The lowest rupture force and energy required to initiate kernel rupture were determined for *Güney Karasi* and *Cakildak*, respectively. Statistical analysis showed that the kernel rupture energy differences between the nut varieties were significant ($P < 0{\cdot}01$).

(5) All the results presented here have shown that nut shell had the highest specific deformation, rupture force, and rupture energy while the kernel had the lowest.

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