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Full Length Research Paper

Effects of moisture content and compression positions on mechanical properties of carob pod (*Ceratonia siliqua* L.)

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Mechanical properties should be investigated for the harvest and post harvest operations of carob pod which is the fruit of carob trees (*Ceratonia siliqua* L.). These properties are pre-requisite for the design and development of harvesting, transportation, storage, and grinding machines used for carob pod. In this study, rupture force, bioyield force, rupture deformation, bioyield deformation, modulus of elasticity and rupture energy were determined for carob pod as functions of moisture content at four different levels of 8.3, 13.2, 14.1, 16.8% wet basis (w.b.) and compression positions of Horizantal1 (H1), Horizantal2 (H2), Vertical1 (V1), and Vertical2 (V2). The biological material test device was used to measure the mechanical properties of carob pod. Results showed that rupture force, bioyield force, modulus of elasticity and rupture energy decreased with increase in moisture content of carob pod. The rupture force ranged from 101.0 to 197.0 N while the bioyield force varies between 84.0 and 159.0 N. The modulus of elasticity changed between 22.5 and 43.8 N mm^{-2}. The range of the rupture energy calculated was between 268 and 419 J. The results showed that rupture force measured at the horizontal positions (H1 and H2) were higher than that of the vertical positions (V1 and V2).

Key words: Mechanical properties, carob pod, rupture, bioyield, modulus of elasticity.

INTRODUCTION

Carob tree (*Ceratonia siliqua* L.) belonging to the *Caesalpinaceae* subfamily of the family Leguminoseae is a perennial plant and widely cultivated in the Mediterranean area (Seçmen, 1974). Carob tree is a drought-resistant, perennial leguminous tree, with beanlike fruit (Owen et al., 2003). Carob has mainly two types; "cultivated" and "wild" (Karkacier et al., 1995). In Turkey, carob tree is naturally cultivated along the 1 750 km coastline from Province of İzmir to Hatay. The total cultivation area of carob tree in the world is 102 939 ha while that of the countries in the Mediterranean coastline is around 83 474 ha (Fao, 2008). In Turkey, based on data obtained from the Turkish Statistical Institute, cultivation area, production and yield of carob tree are 272 ha, 12097 tons year^{-1}, and 51 kg tree^{-1} in 2008, respectively (Tuik, 2008).

The mature fresh fruit is made up of about 90% of pod (known as kibble) and 10% of seed. Several products are produced from the seed and pod (Fletcher, 1997). When the seeds are removed, the pod is further kibbled to various grades for animal feed and even more finely to produce chocolate-like flour that is used in all sorts of carob preparations. The pod of the carob fruit has long been used as a feed for livestock and in human nutrition, including sweets, biscuits and processed drinks, because of its high sugar content (Davies et al., 1971; Khair et al., 2001). Recently, the utilization of products obtained from carob pod especially in pastry and health sector is getting widespread in Turkey.

Battle and Tous (1997) stated that harvesting can be manual or mechanical. In Mediterranean countries, carob groves are mainly hand - harvested by knocking down the pods with the help of long bamboo poles or wooden

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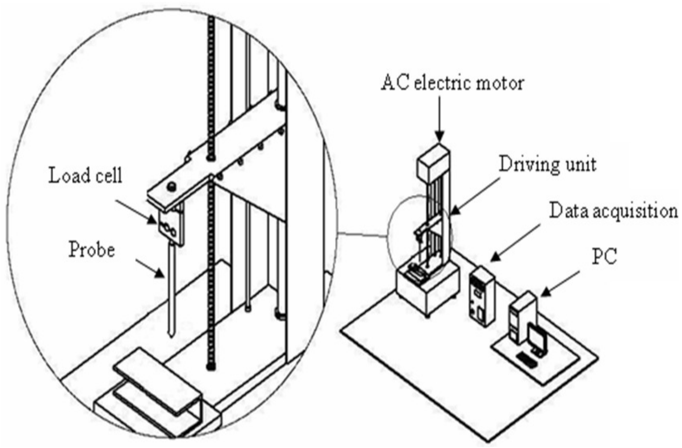

Figure 1. Biological test device.

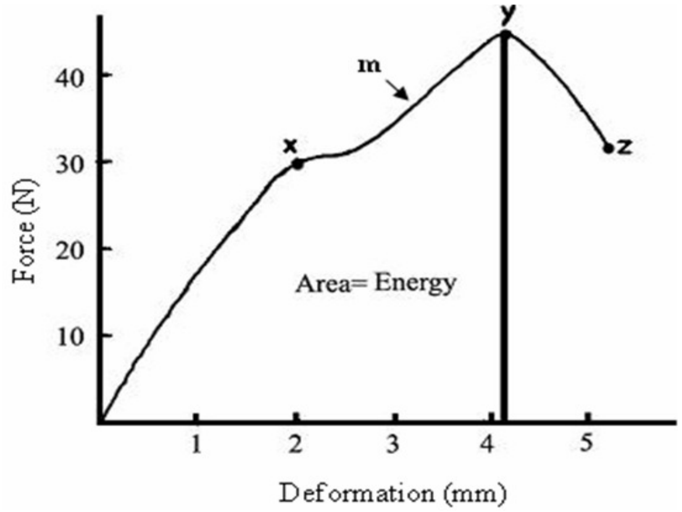

Figure 2. Typical force-formation curves of biological materials during loading: x – bioyield point; y – maximum force point; z – breaking point; m- modulus of elasticity curve (Mohsenin 1986).

sticks and collecting them on fibre nets which are laid out under the trees. This task constitutes the most significant part of the total cost of cultivation since it requires much hand labor, being currently about 30 - 35% of the total production costs. Mechanical harvesting using trunk or branch shakers have not been practiced in most producing countries, mainly because of the small size of most orchards. Most of the carob pods harvested is brought to the processing plant. When carobs arrive, moisture content is variable from 10 to 20% (w.b.) depending on harvesting conditions. Pods require further drying and thus are stored under shelter in dry and ventilated places to reduce moisture content to around 8% (w.b.) and to avoid rotting. Pods are kibbled to separate the two main components; pulp and seeds. Carob pods are crushed mechanically using a kibbler, then are separated from the kernels. This first coarse grinding can be followed by fine grinding of the pod pieces (kibbles) either at the same plant or at the feed or food factories. In order to improve the mechanization (harvesting, storage and processing) of carob pod, mechanical properties of it should be investigated.

These parameters are pre-requisite for the design and development of processing of carob pod. In recent years, mechanical properties have been studied for various crops such as cumin seed (Singh and Goswami, 1998), macadamia nut (Braga et al., 1999), Africa breadfruit seeds (Omobuwajo et al., 1999), terebinth fruits (Aydin and Ozcan, 2002), locust bean seed (Ogunjimi et al., 2002), shea nut (Olaniyan and Oje, 2002), hazelnut (Guner et al., 2003), walnut (Koyuncu et al., 2004), sunflower stalk (Ince et al., 2005), pine nuts (Ozguven and Vursavuş, 2005), cucurbit seeds (Milani et al., 2007), faba bean (Altuntaş and Yildiz, 2007), almond (Aktaş et al., 2007), jujube (Akbolat et al., 2008), sesame stalk (Yilmaz et al., 2009) and safflower stalk (Ozbek et al., 2009). However, studies on mecha-nical properties of carob pod is limited and much less is known of how the moisture content of carob pod and compression positions affect its mechanical properties. Therefore, the objective of this study was to determine the mechanical properties namely, rupture force, bioyield force, rupture deformation, bioyield deformation, modulus of elasticity, and rupture energy, as affected by moisture content and four compression positions.

MATERIALS AND METHODS

In this research, carob pod which is the fruit of carob trees (*C. siliqua* L.) that grow wildly in Antalya province of Turkey were used to determine the mechanical properties at four different moisture contents and four compression positions. The moisture content of carob pods harvested in the 2009 season were 8.3% (w.b.) with a standard deviation of 0.4% (w.b). To examine the effect of different moisture content values, the certain amount of distilled water was added to the samples of carob pods. Twenty samples of carob pod for each moisture content were prepared. The resulting moisture contents were 13.2, 14.1, and 16.8% (w.b.). Initial moisture content of each carob pod was determined using oven method at 70 ± 2°C until a constant weight was reached (Yağcıoğlu, 1999). Then, the samples of carob pod at different moisture contents were stored at 0°C and 60 - 65% relative humidity in plastic bags (moisture tight) during the tests.

Figure 1 show the biological material test device used to determine mechanical properties of carob pod (Yilmaz et al., 2009). The general pattern of plant tissue mechanical response shows an initially linear stress-strain relationship, or elastic response, till a critical deformation level. The straight-line slope gives the small strain or initial modulus. At a greater deformation level, as a consequence of sample fracture or failure, the stress decreases at characteristic strain and stress values, which depend mainly on turgor pressure of tissue and failure mode during compression (Mohsenin, 1986) (Figure 2). The computer aided system had three main components: a stable forced and moving platform (slot and probe), a driving unit (electronic variator) and a data acquisition (load cell, PC card and software) system. Data acquisition system collects data at 10 Hz. The load cell capacity was 2 kN. Its accuracy was ±0.2% of full scale. A curve-ended cylindrical probe, 8 mm in diameter, was used to compress carob pod at 7 mm min^{-1} defined

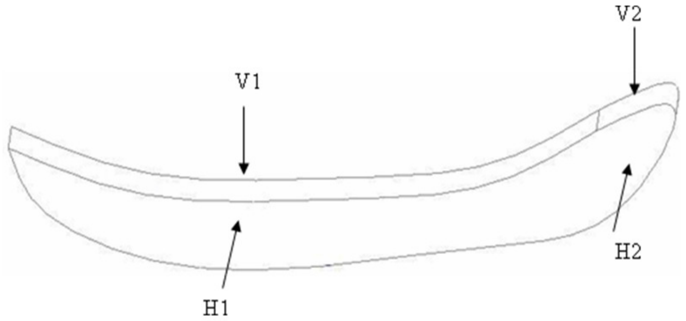

Figure 3. Schematic drawing of four compression positions designated for carob pod showing the locations of force applied.

Table 1. Some physical properties of carob pod.

Parameters (mm)	Mean	Standard deviation
Length	177.17	11.85
Width	23.20	1.32
Thickness	9.58	0.62

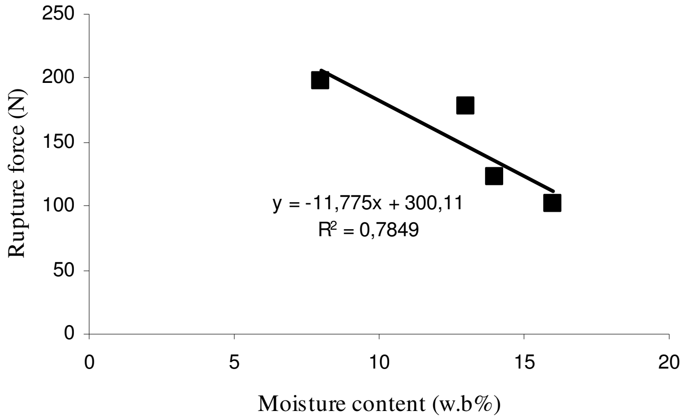

Figure 4. Correlation between the rupture force and moisture content of carob pod.

as penetration speed (Asabe, 1993). The force was measured by using a strain-gage load cell. A force time record was obtained up to the failure of the specimen. With the use of a computer software program, force as a function of deformation was graphically recorded during the experiments. The bioyield force, rupture deformation, bioyield deformation, modulus of elasticity and rupture energy were determined directly from the chart by measuring the area under the force - deformation. Figure 2 shows a typical force-deformation curve for compressed carob pod. The energy was determined directly from the chart by measuring the area under the force deformation curves. Four compression positions of carob pod are shown in Figure 3. These are named as Horizontal1 (H1), Horizontal2 (H2), Vertical1 (V1), and Vertical2 (V2). To determine the average dimensions of each carob pod, a sample of 80 carob pods was randomly selected and measured by digital micrometer with an accuracy of 0.01 mm. A completely randomized design was selected for the experiment. The differences among means were compared by Duncan's Multiple Range Test (probability P<0.05).

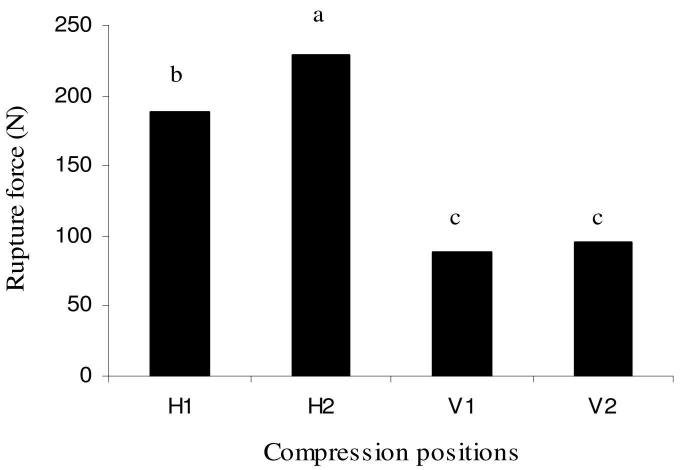

Figure 5. Effects of compression positions on rupture force applied to carob pod.

RESULTS AND DISCUSSION

For all the studies reported here, in order to determine the relationships between moisture content and mechanical properties, carob pods were grouped based on moisture content of carob pods regardless of compression positions. However, to identify the relationships between compression positions and mechanical properties, carob pods were grouped based on compression positions of carob pods regardless of moisture content. It should be noted that only carob pod, which is known as "kibble", was considered for the measurement of mechanical properties during the compression tests. The mean and standard deviation of carob pod length, width, and thickness are presented in Table 1. Figure 4 shows rupture force as a function of moisture content regardless of compression positions. The rupture force ranged from 101.0 to 197.0 N. The rupture force decreased with increase in moisture content. The result is in harmony with those reported by Ozbek et al. (2009), Ince et al. (2005) and Mohsenin (1986). The relationship between moisture content and rupture force was expressed by a linear equation with a value for R^2 of 0.78. The rupture force changing with the compression positions regardless of moisture content with statistical grouping is given in Figure 5. The response of rupture force on compression positions was found to be statistically significant (P<0.05). The highest rupture force (228.0 N) applied was measured at H2 position among all the compression positions. Although there is no literature about mechanical properties of carob pod, the reason why the highest rupture force was measured at H2 can be explained as follows:

1. Visual inspection showed that the distribution pattern of seed inside of carob pod is not homogeneous, especially through the tip of carob pod and the surface corresponding to H2 compression position has possibly

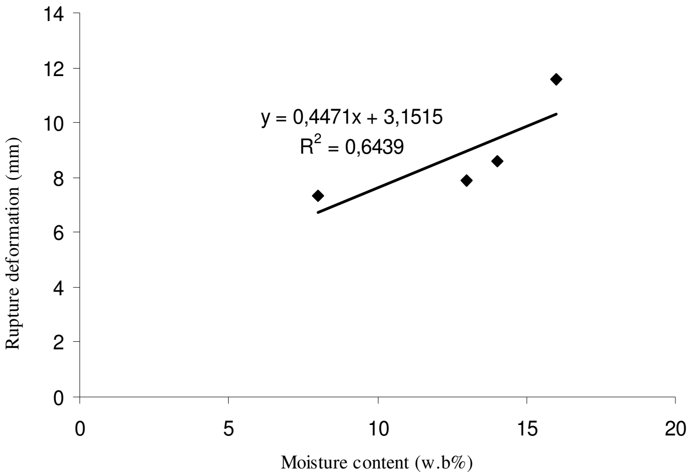

Figure 6. Correlation between rupture deformation force and moisture content of carob pod.

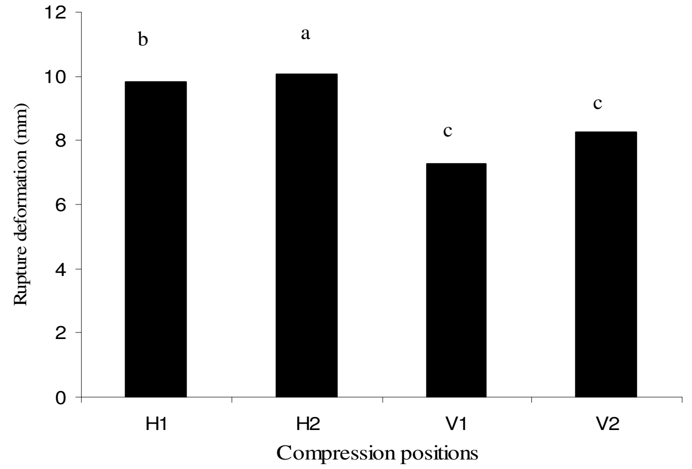

Figure 7. Effects of compression positions on rupture deformation measured from carob pod.

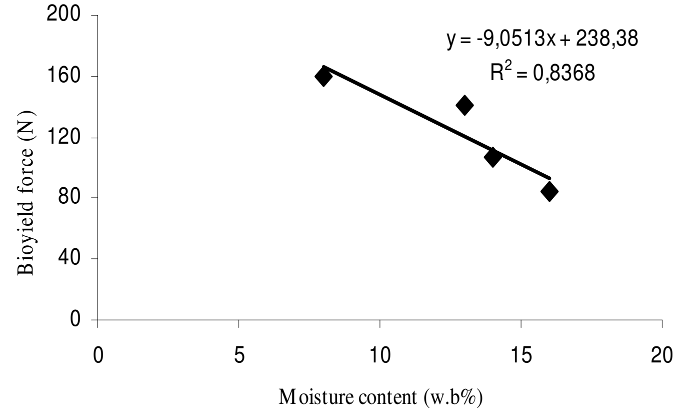

Figure 8. Correlation between bioyield force and moisture content of carob pod.

more seeds inside of carob pod and thereby creating possibly higher internal resistance for rupturing force at H2 compression position.

2. It might be due to the differences in the texture of carob pod. For example, the thickness at the tip of the carob pod is higher than that of middle. This may create resistance for rupturing force at the compression position of H2.

Rupture deformation changes based on the properties of biological materials. It depends on structure of biological material and cells' pores (Persson, 1987). Rupture deformation is irreversible and visible fracture form. The experimental results for rupture deformation at different moisture content levels are plotted in Figure 6. The result showed that rupture deformation ranged from 7.3 to 11.6 mm and increased with increase in moisture content of carob pod. Result of regression analysis yielded values for the coefficient of determination R^2 of 0.64 indicating relatively weak relationship between rupture deformation and moisture content. This trend can be attributed to the fact that at higher moisture contents, carob pod were softer and tended to flatten easily under load and thus subjected to greater deformation. A similar trend was observed for shea nut (Olaniyan and Oje, 2002). Furthermore, Singh and Goswami (1998) found that the deformation for cumin seed increased linearly with increasing moisture content. The effect of compression positions on rupture deformation is given in Figure 7. Rupture deformation changed from 7.3 to 10.1 mm. Statistical analyses showed that the effect of rupture deformation on compression positions was statistically different ($P<0.05$). Additionally, the rupture deformation measured at the horizontal positions (H1 and H2) were higher than that of the vertical positions (V1 and V2).

Mohsenin (1986) stated that bioyield point is a point on force - deformation curve at which there occurs an increase in deformation with a decrease or no change of force. In some agricultural products, the presence of bioyield point is an indication of initial cell rupture in the cellular structure of the material. Ozbek et al. (2009) pointed out that the bioyield force is dominant and characterizing feature of each force-deformation curve for the compression tests. Plot in Figure 8 shows a decrease in the bioyield force with increasing moisture content regardless of compression positions. The results are parallel to those reported for safflower stalk (Ozbek et al., 2009). The relationship was expressed by a linear equation with values for R^2 of 0.84 indicating a strong relationship between bioyield force and moisture content. The values of bioyield force were determined as 159.0 and 84.0 N at the moisture content of 8.3 and 16.8% (w.b.), respectively. Compression positions also affected the bioyield force measured (Figure 9). The highest bioyield force was measured as 175.0 N at H2 compression position while that of the lowest was 75.0 N at V1 compression position. Differences among compression

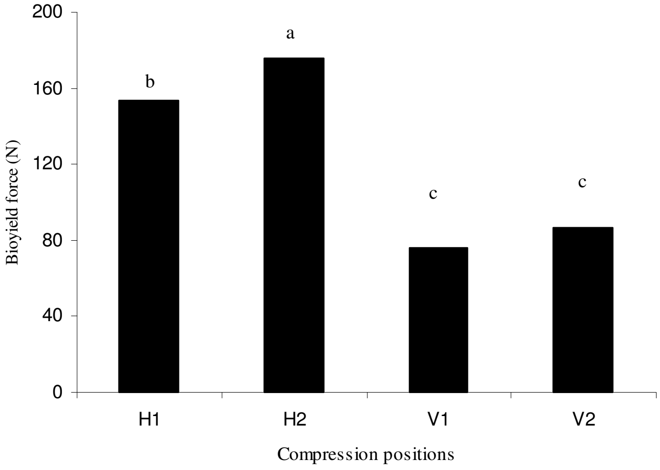

Figure 9. Effects of compression positions on bioyield force measured from carob pod.

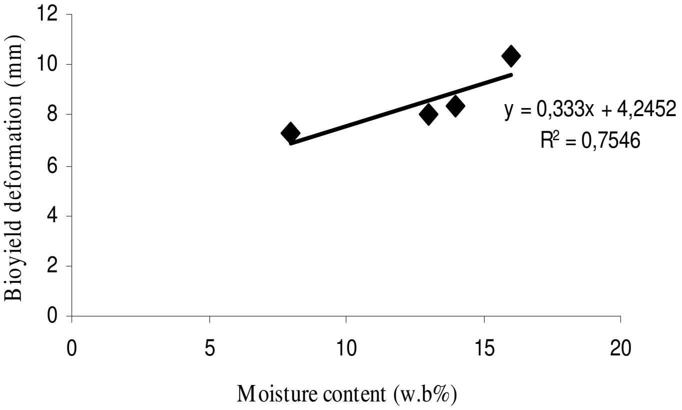

Figure 10. Correlation between bioyield deformation and moisture content of carob pod.

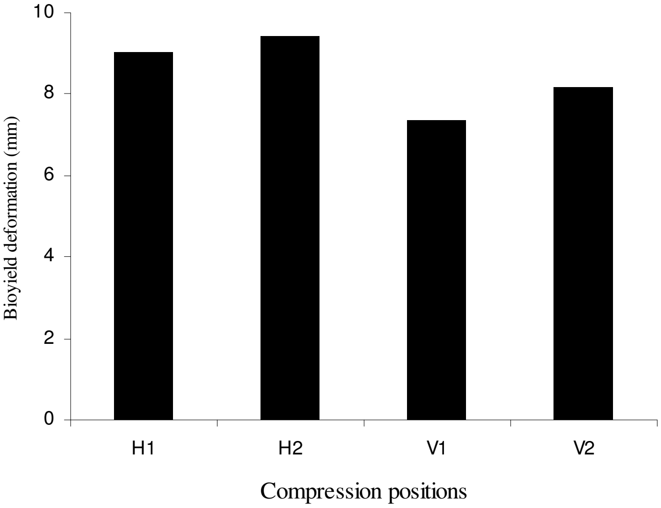

Figure 11. Effects of compression positions on bioyield deformation measured from carob pod.

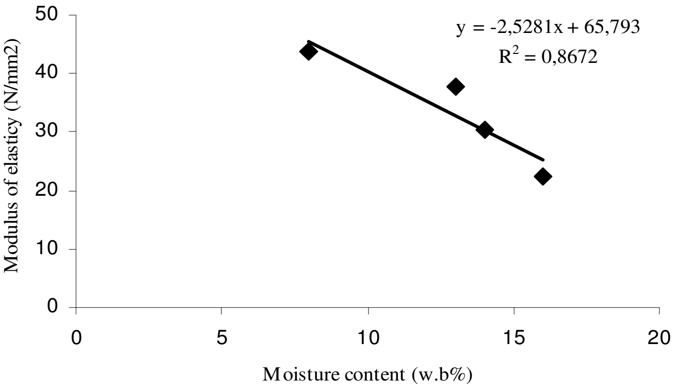

Figure 12. Correlation between modulus of elasticity and moisture content of carob pod.

positions were also statistically significant ($P<0.05$). Bioyield deformation which occurs at the bioyield point is a measure of yield as in millimeters. The change in bioyield deformation as a function of moisture content is given in Figure 10. Bioyield deformation was positively correlated with the moisture content with a R^2 of 0.75. The results are in agreement with those reported for safflower stalk (Ozbek et al., 2009). The highest (10.3 mm) and the lowest (7.3 mm) bioyield deformation occurred at the moisture content of 16.8 and 8.3% (w.b.), respectively. The relationship between bioyield deformation and compression positions is given in Figure 11. Despite the fact that the highest bioyield deformation existed for H2 position, a Multiple's Duncan Range test applied to the data showed no significant differences among compression positions. Mohsenin (1986) stated that modulus of elasticity is the ratio of stress to strain within the elastic range of the material. It is an indication of rigidity and stiffness of the material. Experimentally determined relationship of modulus of elasticity as a function of moisture content is given in Figure 12. Result of regression analysis yielded values for the coefficient of determination, R^2, of 0.86. Increasing moisture content decreased the modulus of elasticity of carob pod. Similar decreasing trends were reported for safflower (Ozbek et al., 2009), for sunflower (Ince et al., 2005) and for alfalfa stems (Galedar et al., 2008). Modulus of elasticity ranged from 43.8 to 22.5 N mm^{-2} in this study. The change of modulus of elasticity based on compression positions is given in Figure 13. Modulus of elasticity at the compression position of H2 was measured as 45.8 N mm^{-2} while that measured at V1 was 21 N mm^{-2}. The effects of modulus of elasticity on compression positions was found to be statistically significant ($P<0.05$). Rupture energy calculated changed between 268 and 419 J at the moisture content of 8.3 and 16.3% (w.b), respectively (Figure 14). Rupture energy decreased linearly with increase in moisture content ($R^2=0.87$). The increase in rupture energy with decreasing moisture content of carob pod

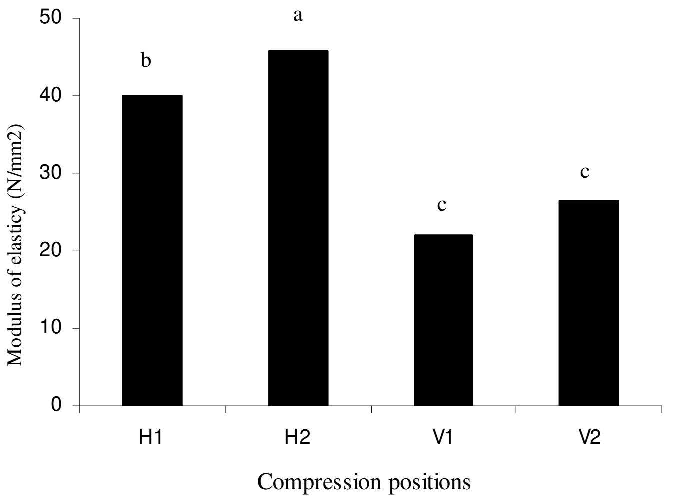

Figure 13. Effects of compression positions on modulus of elasticity of carob pod.

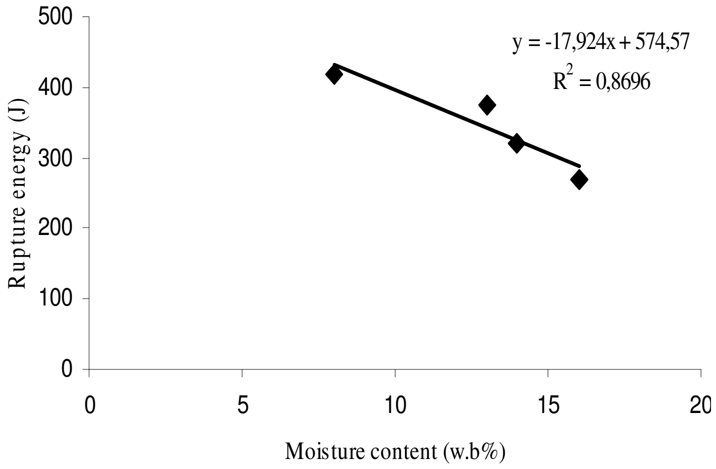

Figure 14. Correlation between rupture energy and moisture content of carob pod.

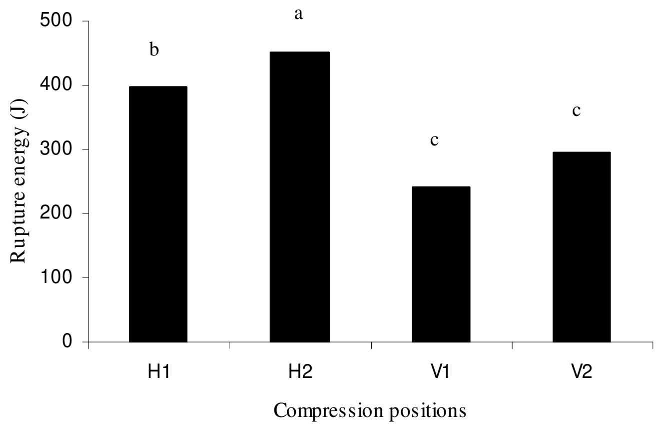

Figure 15. Effects of compression positions on rupture energy measured from carob pod.

may be due to hardening of the carob at lower moisture contents. The results are in agreement with those reported by Singh and Goswami (1998) (a decrease in energy absorbed by cumin seed with increase in moisture content). Furthermore, Aktas et al. (2007) obtained the similar trend for some almond cultivars. Statistical analysis showed that, the effects of the rupture energy and compression positions were significant at 0.05 probability level (Figure 15). Rupture energy was calculated as 451 and 240 J at the compression positions of H2 and H1, respectively.

Conclusion

In this study, the mechanical properties (rupture force, bioyield force, rupture deformation, bioyield deformation, modulus of elastic and rupture energy) of carob pod which is the fruit of carob trees (*C. siliqua* L.) that grow wildly in the Antalya district of Turkey were determined as affected by different moisture content and compression positions. Rupture force, bioyield force, modulus of elasticity and rupture energy decreased with increase in moisture content of carob pod. However, at the higher moisture contents, the carob pods are getting sticky. At the other side, most of the carob pods harvested are brought to the processing plant with the moisture content of 10 - 20% (w.b) depending on harvesting conditions. These criterions in terms of moisture content should be considered for the design and development of the processing machines of carob pod. This study showed that the rupture force measured at the horizontal positions (H1 and H2) were higher than that of the vertical positions (V1 and V2). This indicates that carob pods could be piled up or stocked horizontally for the purpose of transportation and storage to avoid mechanical damage whereas it could be vertically positioned for the grinding process.

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