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Bulk Peanut Shell Behavior under Static Loads and the Associated Physico-Mechanical Properties

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In order for the peanut shell waste to have an economic value, it should be processed mechanically. Among others, for instance, utilization of peanut shells as a fuel source or insulation material requires them to be compressed. Thus, for a rational design of such machinery, there is a need to know the behavior of peanut shells under compressive static loads and the associated physico mechanical properties. To those ends, experiments were carried out, using the local Turkish cultivars Osmaniye, Silifke, Anamur and Antalya. Mathematical models for force-deformation, pressure-strain and pressure-density relationships were obtained from the test data. Linear and non-linear behaviors in the first, third and second regions of the test domain were determined, respectively. Limiting values of pressure, density, stiffness, bulk moduli, compression ratio and compression energy per volume were estimated. For the cultivars tested, stiffness values varied between 19.7 and 52.6 N mm^{-1} in the first region, between 12402.0 and 5111.2 N mm^{-1} in the third region. Bulk moduli ranged from 0.184 to 0.471 N mm^{-2} in the first region, and from 46.886 to 110.182 N mm^{-2} in the third region. Compression energy per volume and compression ratio were found between 0.1976 and 0.2916 N mm.mm^{-3}, and between 4.0 and 4.4, respectively.

Key Words: compression tests, peanut shell behavior, physico-mechanical properties

INTRODUCTION

Peanut is an important economic crop grown in China, India, Nigeria, the United States and Turkey (FAO 2015). Peanut, being utilized essentially for its kernel as a food source, mostly enters trade in the form of kernel (Carley 1983). However, there is another important part of the peanut, which accounts for 25% of the total mass, namely, the peanut shell. Peanut shell can be a significant potential source of energy as a possible substitute of fossil fuel, which pollutes the environment and can also contribute to the removal of the waste disposal problem (Fasina 2008). The economic value of peanut shells can further be multiplied through its utilization as heat and sound insulation materials in buildings (Woodroof 1973). In order to make use of this economic potential for the indicated purposes effectively, the products have to be transformed into briquettes or plates by compression.

There are studies associated with different aspects of peanut shells. Chin and Siddiqui (2000) have indicated that peanut shell has a relatively high calorific value among other biomaterials such as sawdust, rice husk and palm fiber. It has been experimentally proven by the same researchers that the relaxed density of peanut shell is relatively stable among other biomaterials, once a critical pressure is exerted on its bulk. Peanut shell, being a part of biomass which constitutes a renewable energy resource, is proposed to be a substitute for fossil fuel amounting to as much as 30% of petroleum consumption in the U. S. (Perlack et al. 2005; Fasina 2008).

Direct extraction of energy, such as burning agricultural waste with low bulk densities, is not very effective in homes and industry. In case direct use of this waste is preferred, problems associated with transportation, storage, handling, and processing arise (Al -Widyan et al. 2002; Demirbaş et al. 2004; Fasina 2008). To overcome these kinds of problems, the necessity of briquetting peanut shells is to be recognized. Briquetting is the process of compressing the fragmented material with size greater than 25 mm diameter. Biomass densification, which is also known as briquetting of agro residues, has been mentioned to improve the combustion characteristics (Grover and Mishra 1996). Pelletizing is another method of increasing the bulk density of biomass by mechanical pressure. Pellets have a high bulk density (more than 600 kg m^{-3}) for efficient transport and a safe storage (Mani 2006). Theerarattananoon et al. (2011) and Tilay et al. (2015) have emphasized the importance of evaluating the physico-mechanical properties of agricultural wastes for their proper use in the pellets. The knowledge of peanut shell behavior during the compression and molding process is crucial in this respect.

Many studies have been done by some researchers regarding the physical and physico-mechanical properties of hulled peanut. For instance, Akcali et al. (2006) and Aydın (2007) have experimentally investigated the geometrical shape, the specific mass and coefficient of friction. Furthermore, behavior of hulled peanut against different types of loading like static, fatigue and impact loads was studied. For the fatigue loading linear and logarithmic models between shelling pressure and the number of load cycles were obtained (Guzel et al. 2005). The peanut bulk was subjected to static loads, leading to the determination of shelling pressure, bulk modulus, their corresponding breakage percentages and the required energy for shelling (Guzel et al. 2007). In the case of impact loads, the shelling pressures were determined (Ugurluay et al. 2013).

In the literature, there are studies mathematically modelling the mechanical behavior of the agricultural materials like common sunflower, jatropha, garden pea, common bean, wood chips, and waste paper chips under compression loading (Herak et al. 2011, 2014). Some other studies aimed at determining mechanical behavior and the associated characteristics of agricultural material like sunflower seeds and rapeseeds within the context of oil extraction machinery (Sigalingging et al. 2015; Divišová et al. 2014). However, to the best of our knowledge, the behavior of shells of several different peanut types under compressive static loading has not been investigated. Without these data of peanut shells, it is not possible to design briquetting machines based on a rational approach. In order to handle this design effectively on a quantitative basis, for instance, numerical data about pressure levels, energy requirements against desirable densities are to be provided to the design process. Thus, it is the primary objective of this paper to understand how the bulk of peanut shells responds to compressive forces under well-defined conditions. Within this context, compression tests were carried out to find out force-deformation, pressure-strain and pressure-density characteristics. Resultantly, physico-mechanical properties of peanut shells such as critical values of pressure and corresponding densities, stiffness, bulk modulus and energy per volume were determined from the experimental results.

MATERIALS AND METHODS

Four local cultivars of peanut were used in the experiments. These are Osmaniye, Silifke, Anamur and Antalya types which are defined in Turkish Standards (TS -310 1972). The test samples were selected randomly from each of the peanut types. The average moisture content of the test samples was determined as 5 ± 0.2% (d.b.) according to the procedure shown in Mohsenin (1980).

Compression tests involving three trials were done with a 20-ton universal testing machine (Model-91/1996, ALŞA Ltd., Istanbul-Turkey) with a resolution of 1 kgf under a constant loading rate of 200 kgf s^{-1}. Some parts of the compression apparatus used in the experiment set-up are schematically shown in Figure 1. The empty steel cylinder which has 90 mm diameter and 100 mm height, was fitted with the bottom plate in Figure 1. The pressing piston was placed on them.

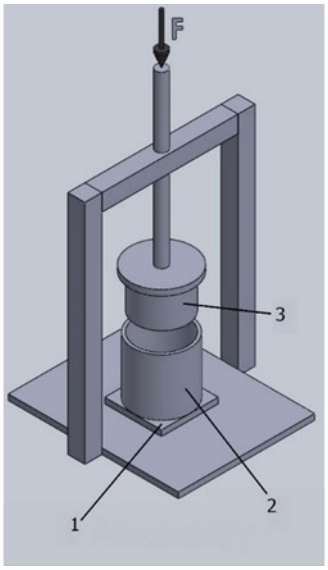

Fig. 1. Compression fittings of the experiment set-up: 1- Bottom plate, 2- Empty cylinder, 3- Pressing piston.

The masses (m) of peanut shells were measured by the weight scale with a resolution of 0.1 g. Then the empty cylinder was filled with peanut shells, which was taken from the mechanical shelling machine. The cylinder was shaken until the surface was flattened, followed by the measurement of the initial height (h_0). The static loads were applied at a constant rate (200 kgf s^{-1}) on the shells through the piston and the corresponding heights (h_1) in the cylinder were measured.

From the test results, the following calculations were performed. Pressure (p) values were obtained by dividing the applied forces (F) by the piston area (A). Density (ϱ) was calculated by dividing the sample mass by its deformed volume. Deformation (Δh) was computed by taking the difference between the initial height (h_0) and the position (h_1) of the piston under load. Strain (ε) was evaluated through the division of deformation by the initial height. Compression ratio (λ) was, in general, defined as the ratio of initial height to the displaced height (h_1). However, its maximum value was considered to be of significance. Pressure, density, strain, and compression ratio expressions are shown below:

$$p = F/A \qquad (1)$$

$$\varrho = m/(A.h_1) \qquad (2)$$

$$\varepsilon = \Delta h/(\ h_0\ ) = (h_0 - h_1)/h \qquad (3)$$

$$\lambda = h_0/h_1 \qquad (4)$$

When the test data are plotted to yield force-deformation, pressure-strain and pressure-density relationships by means of Eqns. (1)-(4), as shown in Figure 2, three distinct regions in which behaviors could be modelled differently are determined. In the first and third regions, linear behaviors are observed, while in the second region clearly a nonlinear behavior is seen (Figure 2). From the slopes of lines in the first and third regions of force-deformation relationships, stiffness (k) values are calculated. Similarly bulk modulus (B) is evaluated as the slopes of lines in the first and third regions of pressure-strain relationships. The area under the pressure-strain curve gives the value of energy per volume required for compressing the peanut shell with a corresponding density. The curve is integrated between the initial and final test points to find the area.

Considering force-deformation (F-Δh), pressure-strain (p-ε) and pressure-density (p-ϱ) relationships, when the ordinate and abscissa are represented by y and x, respectively, the general model for all these relationships can be given as such;

$$y = a_0 + a_1x^1 + a_2x^2 +\_\ \_\ \_+ a_nx^n. \qquad (5)$$

In the first and third regions linear regression and in the second region nonlinear regression were implemented, through the use of MS Excel, to estimate the values of the coefficients in Eq. (5), based on the compression test data. All the relevant data points are entered to the MS Excel data sheet. Command "insert chart" button is activated. Command "add trendline" button is used. "Display the equation on the graph" and "display the R squared value on the graph" options are selected. The equation that gives the highest R square value is found by trying all the options. The coefficients in this equation are presented as model coefficients. The limiting value of the power (n) of the independent variable in Eq. (5) was determined in such a way that the two consecutive results differed from each other by a negligible change in the correlation coefficient.

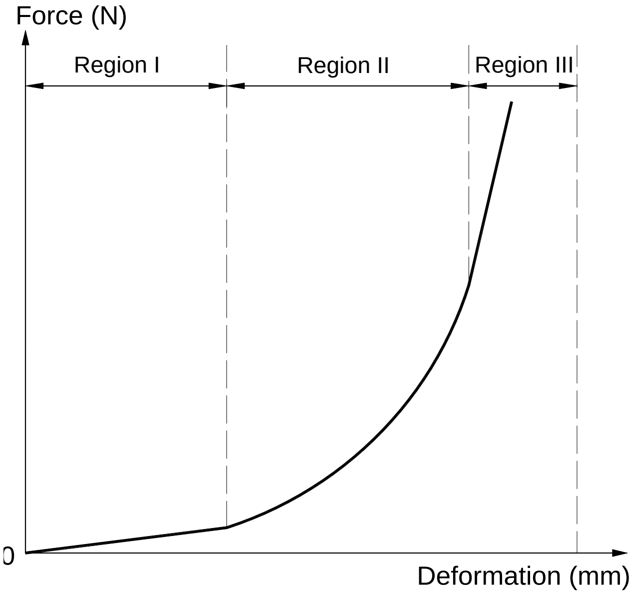

Fig. 2. Force-deformation relationship.

RESULTS AND DISCUSSION

Some of the significant results obtained at the end of compression tests are summarized in Table 1, which displays the amount of shell mass subject to compression inside the cylinder, the first and last heights together with the initial and final volumes of the shell mass measured during the experiments as well as compression ratio determined resultantly.

The whole force-deformation curve seems suitable for dividing it into three distinct regions. By considering three consecutive points linear region, where the slope is constant, ends at the midpoint when the third point has a different slope than the first two points; the midpoint becomes the end point of nonlinear region, where the

Table 1. Resulting values of the peanut cultivars in tests.

	Osmaniye	Silifke	Anamur	Antalya
Pressed shell mass (g)	26.6 ± 0.5	26.8 ± 1.2	26.4 ± 1.4	25.1 ± 0.9
The first height of the shell mass (mm)	59 ± 1.0	59 ± 3.5	60 ± 1.5	57 ± 1.5
The last height of the shell mass (mm)	14 ± 0.1	14 ± 1.0	14 ± 0.5	14 ± 0.0
The first volume of the shell mass (mm^3)	375 850	372 500	378 500	360 000
The last volume of the shell mass (mm^3)	89 800	89 100	85 900	89 600
Compression ratio, ε	4.2	4.2	4.4	4.0

slope is variable, when the last two points have the same slope. In Region I, it is observed that force vs. deformation relationship is a linear one, Figure 3. Due to the complex geometry of peanut shells, large space between the shell pieces appears to have been removed with a small force leading to large deformations in the whole bulk, as is clear from Figure 3. Region II displays a nonlinear relationship between the compressive force and resulting deformation. Nonlinear variation is explained by the fact that crushing of shells occurs in this region. In Region III, a linear behavior with a large slope is noticed. Large slope is attributed to the complete integration of the shells into a solid body, Figure 3.

The force-deformation curves of all types (Osmaniye, Silifke, Anamur and Antalya) used in the experiments are shown in Figure 4. All cultivars behave very similarly as can easily be seen from Figure 4. No statistically significant difference was found between force and deformation values among cultivars. (Anova test results for force df:76; Sig.:0.888, for deformation df:76; Sig.:0.804). Tukey HSD test results for force Sig.:0.876 and for deformation Sig.:0.773.

Behaviors of different types in each region are modelled separately in accordance with Eq. (5). The numerical values of the coefficients in Eq. (5) with the corresponding coefficient of determination (R^2) for all regions are collected in Table 2. The fact that the correlation coefficient varies between 0.97 and 1 implies a very good agreement between test results and their representative mathematical models. In all the curves, the limiting value of power of the polynomial is 3.

Compression of agricultural waste material was also handled by some researchers such as Chin and Siddiqui (2000), Husain et al. (2002), Oladeji (2012), Oyelaran et al. (2014) and Tilay et al. (2015) who generally studied the mechanical strength and thermal values of briquettes and pellets which were obtained through the compression. However, the compression work was not examined in detail in the mentioned studies. Nevertheless, there are other works which aimed at determining and comparing

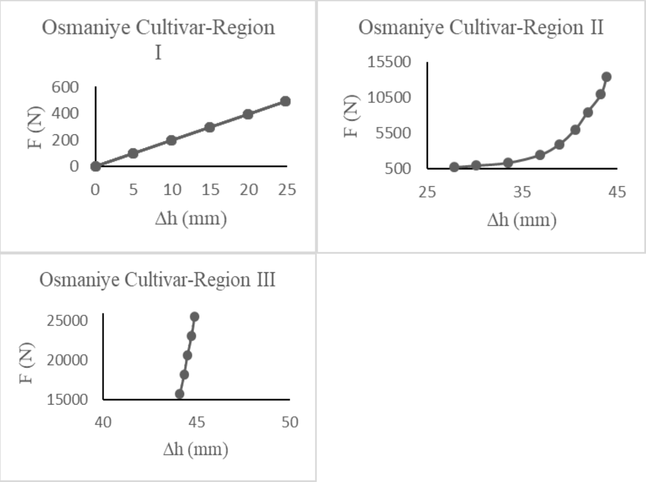

Fig. 3. The representative behavior of Osmaniye cultivar (F-Δh).

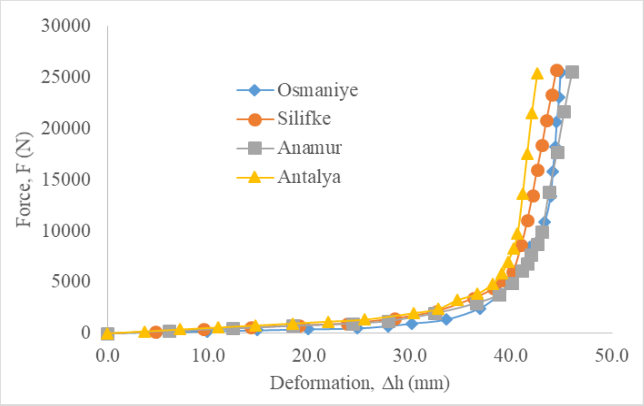

Fig. 4. The force-deformation curves of the cultivars.

Table 2. Force-deformation model and associated coefficient of determination (R^2).

Cultivar	Region	a_0	a_1	a_2	a_3	R^2	Domain
	I	0.093	19.774	0	0	1	<23.6
Osmaniye	II	58.935	-557.560	17 639	-185 444	0.99	23.6-42.5
	III	531 629	12 402	0	0	0.99	>42.5
	I	0.773	41.326	0	0	1	<23.8
Silifke	II	-310 404	28 576	-872.350	8.899	0.97	23.8-40.2
	III	201 597	5 111.200	0	0	1	>40.2
	I	3,153	40.241	0	0	1	<24.4
Anamur	II	-221 138	20 398	-622.560	63.472	0.99	24.4-42.6
	III	215 134	5 229.600	0	0	1	>42.6
	I	0.319	52 655	0	0	1	<25.5
Antalya	II	-523 360	46 888	-1397.100	13.919	0.99	25.5-40.3
	III	322 163	8 165	0	0	1	>40.3

the mechanical behavior and the associated characteristics of jatropha seed, rapeseeds, and sunflower seeds (Sigalingging et al. 2015; Divišová et al. 2014; Herák et al. 2014; Kabutey et al. 2012). Although compression tests in this research have been performed on peanut shells, mechanical behavior resulting from the tests is similar to the ones displayed in the aforementioned literature. The data deduced from the peanut shell tests are intended to be supplied to the design of peanut shell processing machinery.

Stiffness is the ratio of the applied force to change in deformation in the region where a material exhibits linear behavior. The numerical values of stiffness calculated from the slopes of lines in the first and third regions of force-deformation curves for each cultivar are collected in Table 3. Stiffness of the bulk shell is seen to vary between 19.7 and 52.6 N mm^{-1} depending on the cultivar. On the other hand, the solid shells corresponding to the third region have stiffness values ranging from 5111.2 to 12402.0 N mm^{-1}. The numerical values indicate that while less force per unit deformation is needed in the first region, relatively high force is required per unit deformation in the third region. There was statistically significant difference between values among cultivars both in Region 1 and Region 3. (ANOVA test results for Region 1 df:11; Sig.:0.001, for Region 3 df:11; Sig.:0.022). No statistically significant difference was found in each Region (Tukey HSD test results for Region 1 Sig.:0.193 and for Region 3 Sig.:0.152).

Table 3. Stiffness values of different peanut cultivars.

Cultivar	Stiffness (Region I), k (N/mm)	Stiffness (Region III), k (N/mm)
Osmaniye	19.7	12 402.0
Silifke	41.3	5 111.2
Anamur	40.2	5 229.6
Antalya	52.6	8 165.0

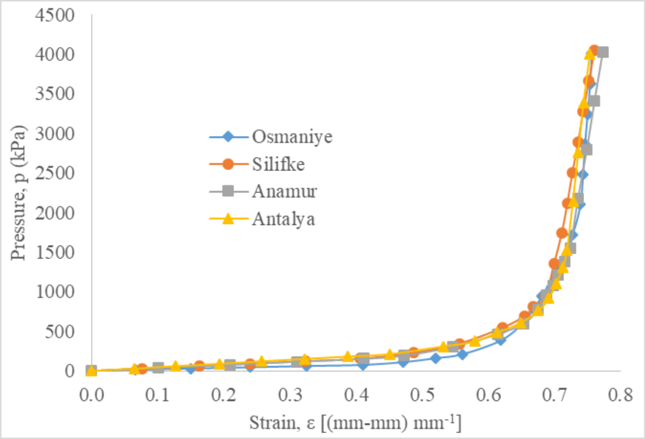

Fig. 5. Pressure-strain curves of the cultivars.

Compression test results regarding force-deformation relationships are transformed into pressure-strain relationships by means of Eq. (1) and (3). Resulting pressure-strain curves for all cultivars used in the experiments are displayed in Figure 5. The behavior of the shells resembles those observed in force-displacement curves with regard to pressure-strain relationships, which means that pressure varies linearly with respect to strain in the first and third regions while a nonlinear variation is observed in the second region. The model coefficients are collected in Table 4. As can be seen from the coefficient of determination that varies between 0.97 and 1, the models accurately represent the experiment results. No statistically significant difference was found between pressure and strain values among cultivars (ANOVA test results for pressure df:76; Sig.:0.887, for strain df:76; Sig.:0.937 and Tukey HSD test results for pressure Sig.:0.874 and for strain Sig.:0.927).

The slope of the lines in Region I of the pressure-strain

Table 4. Pressure-strain model and associated coefficient of determination (R^2).

Cultivar	Region	a_0	a_1	a_2	a_3	R^2	Domain
Osmaniye	I	1.886	184.710	0	0	0.99	<0.41
	II	27 918	158 012	297 415	187 377	1	0.41-0.73
	III	79 478	110 182	0	0	0.99	>0.73
Silifke	I	0.780	378.310	0	0	1	<0.40
	II	52 109	280 045	499 052	297 044	0.97	0.40-0.69
	III	31 610	46 886	0	0	1	>0.69
Anamur	I	0.410	371.940	0	0	1	<0.41
	II	35 943	196 236	354 753	214 328	0.99	0.41-0.71
	III	34 691	50 069	0	0	1	>0.71
Antalya	I	0.126	471.530	0	0	1	<0.32
	II	10 494	65 168	131 581	88 691	0.98	0.32-0.71
	III	50 617	72 494	0	0	0.99	>0.71

curves, calculated as bulk modulus of peanut shells for each cultivar, are shown in Table 5. The values of bulk modulus in Region I range from 0.184 to 0.471 N mm^{-2}. The small magnitudes of bulk modulus indicate to a significant flexibility of the peanut shell material, thus requiring very small amounts of pressures corresponding to large strains. In general, it can be easily seen from Table 5 that the bulk modulus in Region III is more than at least 120 times that of the first region. The bulk modulus found in Region III can be interpreted as the equivalent of the modulus of elasticity of the solid shells. There was statistically significant difference between values among cultivars both in Region 1 and Region 3 (ANOVA test results for Region 1 df:11; Sig.:0.001, for Region 3 df:11; Sig.:0.021). No statistically significant difference was found in each Region (Tukey HSD test results for Region 1 Sig.:0.192 and for Region 3 Sig.:0.152).

Table 5. Bulk modulus of different peanut varieties.

Cultivar	Bulk Modulus, B (N/mm^2) Region I	Bulk Modulus, B (N/mm^2) Region III
Osmaniye	0.184	110.1
Silifke	0.378	46.8
Anamur	0.371	50.0
Antalya	0.471	72.4

Compression energy per volume is the total energy required for pressing peanut shell against a unit volume. These values, which are obtained by calculating the area under the curve in each region of the pressure-strain curves, are given in Table 6 associated with cultivars used in the experiment. The total compression energy varies between 0.1976 and 0.2916 N mm mm^{-3}. If these values are compared with those of jatropha, common sunflower, common bean and garden pea, which are 0.397, 0.612, 0.110 and 1.331 N mm mm^{-3}, respectively, it will be seen that the values found in peanut shells are consistent with limits of the mentioned materials (Herak et al. 2012). As observed in Table 6, the fact that compression energy required in Region I is very small in comparison with the total compression energy is in full accord with the low values of bulk modulus obtained above. These values are of significance for the design of briqueting systems in estimating their power requirements. There was statistically significant difference between values among cultivars both in Region 1 and Region 3 (ANOVA test results for Region 1 df:11; Sig.:0.003, for Region 3 df:11; Sig.:0.015). There was no statistically significant difference between values among cultivars in Region 2 (ANOVA test results for Region 2 df:11; Sig.:0.173). No statistically significant difference was found in each Region (Tukey HSD test results for Region 1 Sig.:0.183 Region 2 Sig.:0.175 and for Region 3 Sig.:0.341).

Density is a significant physical property that characterizes not only the volume required for storage and transportation but is also an indicator of latent energy. For this reason, pressure-density relationships involve useful information for determining the necessary pressure for a specified density (Fig. 6). Within this context, pressure vs. density relationships are investigated leading to the mathematical models in Table 7. High values of coefficient of determination (R^2) demonstrate that there is a good agreement between the models and the experiment results. As can be deduced from the examination of solid and bulk densities of the peanut shells in Akcali et al. (2006), it is understood that at the end of compression tests, the bulk peanut shell density reaches the value of the solid density of peanut shell. It further implies that the volume occupied by the same amount of peanut shell has been reduced at least four times, indicating to a significant amount of saving in space requirements. No statistically significant difference was found between pressure and density values among

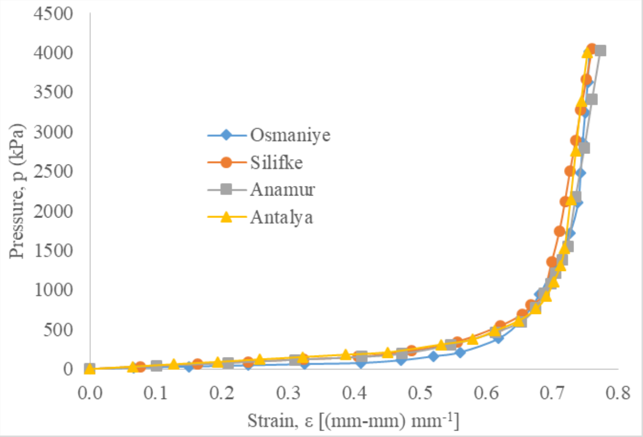

Fig. 6. Pressure-density curves of all cultivars.

Table 6. Compression energy values for different cultivars of peanut shells.

Cultivar	Region I (N.mm/mm^3)	Region II (N.mm/mm^3)	Region III (N.mm/mm^3)	Total Compression Energy, $E_{comp.}$ (N.mm/mm^3)
Osmaniye	0.0158	0.1532	0.0433	0.2124
Silifke	0.0313	0.1265	0.1436	0.3015
Anamur	0.0316	0.1231	0.1368	0.2916
Antalya	0.0245	0.1410	0.0953	0.2610

Table 7. Pressure-density ratio model and associated coefficient of determination (R^2).

Type	Region	a_0	a_1	a_2	a_3	R^2	Domain
Osmaniye	I	-115.58	1 750.1	0	0	0.98	<0.13
	II	7 037.2	-108 773	526 179	-706 331	0.99	0.13-0.27
	III	-22 007	87 654	0	0	0.98	>0.27
Silifke	I	-220.07	3 192.5	0	0	0.98	<0.14
	II	32 767	513 544	0	0	0.98	0.14-0.24
	III	-9 480.9	45 172	0	0	0.99	>0.24
Anamur	I	-249.35	3 655.4	0	0	0.98	<0.10
	II	-2 298.3	45 497	-290 113	673 625	0.99	0.10-0.24
	III	-10 310	46 990	0	0	0.99	>0.24
Antalya	I	-305.09	4 507	0	0	0.98	<0.10
	II	-1 727.8	35 538	-227 286	540 702	0.99	0.10-0.23
	III	-15 315	68 270	0	0	0.99	>0.23

cultivars (ANOVA test results for pressure df:76; Sig.:0.887, for density df:76; Sig.:0.862 and Tukey HSD test results for pressure Sig.:0.874 and for density Sig.:0.876).

CONCLUSION

By the compression tests, it was understood that the peanut shells responded to the pressures applied on it in three different ways, namely, producing large strains in the first region and very small strains in the third region while being crushed in the second region.

Many physico-mechanical properties resulting from the tests done with the peanut cultivars grown in Turkey have been determined. Stiffness values obtained from force-deformation curves vary between 19.7 and 52.6 (N mm^{-1}) in the first region, and between 5111.2 and 12402.0 (N mm^{-1}) in the third region. From the pressure-strain curves, the bulk modulus values in the first and third regions are in the intervals 0.184–0.471, and 46.886–110.182 N mm^{-2}, respectively. The total compression energy per volume was estimated to vary between 0.1976 and 0.2916 N mm mm^{-3}. Shell compression ratio for the variety of peanuts ranges between minimum 4 and maximum 4.4.

The values of the physico-mechanical properties extracted from tests are of great importance in many respects. From the results, it is easily understood that bulk densities approach the values of solid densities after the compression process. This further signifies that a lot of saving is achieved in terms of space by the compression process as much as at least 400%. The impact of this result can be said to cover the important savings associated with the transportation and storage costs of the peanut shell.

By the virtue of available data resulting from this research, it is possible to transfer these significant data to the design process of briquetting machines. For example, mass flow rates as well as pressure forces to forward the pre-determined amount of peanut shell material inside such machinery will have to take into account pressure-density relationships. Pressure-strain relationships together with the accompanying data resulting therefrom, such as energy per volume and bulk moduli, will play important roles in estimating the power requirements and the end product characteristics of the peanut shell briquetting machines.

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