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Estimation of Energy Requirement of *Jatropha Curcas* L. Seedcake Briquettes under Compression Loading

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Abstract: The energy requirement of *Jatropha curcas* L. seedcake of different dimensions (4.5, 5.6, 6.7, 8 and 10 mm) for briquette compaction was investigated under compression loading (100, 200, 300 and 400 kN) using the universal compression-testing machine. The parameters measured and/or calculated were the deformation, thickness, numerical energy and theoretical energy. The statistical analysis results show that compression forces had a significant effect (p-value < 0.05) on the amounts of deformation and thickness, while that of the dimensions of the sample did not. The increase in compression forces increased the numerical energy while that of samples dimensions caused a decrease. Using the tangent curve mathematical model; the force coefficient of mechanical behaviour (kN), the deformation coefficient of mechanical behaviour and the fitting curve function exponent were determined for describing the experimental dependency between the force and deformation curves as well as the numerical energies of densified jatropha seedcake briquettes.

Keywords: jatropha seedcake; briquettes compaction; energy consumption; force-deformation curve; economic value

1. Introduction

Jatropha curcas L. is a multipurpose perennial oil-bearing plant that belongs to the family Euphorbiaceae with a life expectancy of 50 years [1–3]. The production of oil requires de-husking and oil extraction processes [2]. About 50 to 70% of the original seed weight remains as de-oiled seedcake, a by-product after oil extraction. Fruit husk and seedcake have wide-ranging applications as fuel and organic fertilizers or soil conditioners. The seedcake containing high protein can be used as animal feed after further processing and detoxification [2,4]. With the rapid population and economic growth, the energy utilization has been increasing greatly [5]. In the global energy mix, fossil fuels remain the primary energy source that has been associated with the increase of carbon dioxide emissions. The use of renewable energy sources such as biomass is essential in reducing greenhouse emissions and fossil fuel dependency [6–8]. Worldwide, biomass is the third-largest primary energy after coal and oil being the main source of energy for half the world's population [5,9].

Agricultural and industrial residues such as husk, rice bran, rice straw, corn straw, corn cob, bagasse and de-oiled seedcakes can be utilized by the biomass-to-energy conversion processes including but not limited to direct combustion, gasification, pyrolysis, anaerobic digestion, hydrolysis, hydrogenation or fermentation [5,10–12]. These processes, however, are energy and equipment intensive [9,13]. Following the literature, biomass briquetting technologies available include mechanical piston press, screw press, hydraulic press and roller press [9]. Other technologies reported include high-pressure compaction, medium-pressure compaction aided by the heating device and low compaction pressure [14]. Compaction pressure, material moisture content, fraction particle of the initial material, pressing temperature, durability, material or particle density, etc. are important parameters for assessing the quality of densified biomass [15–20]. In the densification process, the mechanical pressure creates bonds between the particulate matter. Natural binders such as lignin, proteins, fats, starch and water-soluble carbohydrates also produce solid bridges between the particles [15]. In order to improve compaction equipment design, reduce energy consumption and improve the quality of products, it is important to understand the mechanical and/or rheological behaviour of biomass materials. The present study aimed at estimating the energy demand and describing the mechanical properties of *Jatropha curcas* L. seedcake of different size distributions under compression loading using a universal compression-testing machine and a pressing chamber with a piston.

2. Materials and Methods

Samples of bulk *Jatropha curcas* L. seedcake of 7.5% moisture content on wet basis were used for the briquette densification. Sample size distributions of 4.5, 5.6, 6.7, 8 and 10 mm were determined using a horizontal sieve shaker (Retsch AS 200, Germany) for 30 minutes at an amplitude of 3.0 mm/"g", according to the standard [21,22]. The moisture content was determined using the standard oven-drying method [23–25]. The universal compression-testing machine (ZDM 50, Czech Republic) was used for the densification process by applying the compression forces F_C from 100, 200, 300 to 400 kN of equivalent pressures P_R from 35.37, 70.74, 106.10 to 141.47 MPa at a constant speed of 5 mm min^{-1}. The initial height of the samples H_i was measured at 60 mm using the pressing vessel of diameter 60 mm (Figure 1). Each sample was replicated twice, making 40 experiments in total.

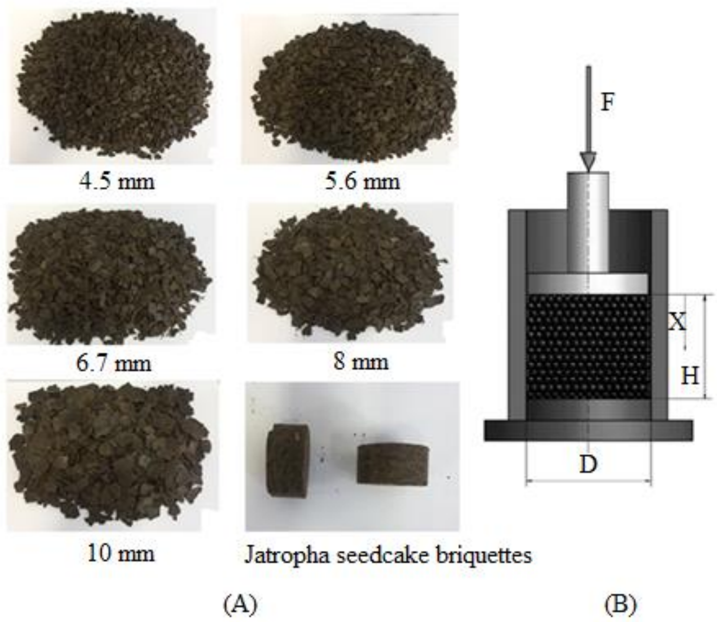

Figure 1. (**A**) Jatropha seedcake of varying size distributions, (**B**) schematic of the pressing vessel with diameter D = 60 mm and a plunger (F—Force, H—Initial height of sample, X—Deformation of samples), reprinted from publication [26].

The following parameters were calculated respectively. The volume of samples was calculated using Equation (1) as follows:

$$V_L = \frac{\pi \cdot D^2}{4} \cdot H_i \quad (1)$$

where V_L is the volume of samples (m^3), D is the diameter of pressing vessel (mm) and H_i is the initial height of samples (mm). The volume of densified briquettes was calculated using Equation (2) as follows:

$$V_B = \frac{\pi \cdot D^2}{4} \cdot T_X \quad (2)$$

where V_B is the volume of densified briquettes (m^3) and T_X is the thickness of densified briquettes (mm). The density of samples was calculated using Equation (3) as follows:

$$D_S = \frac{M_S}{V_L} \quad (3)$$

where D_S is the density of samples (kg m^{-3}), M_S is the initial mass of samples (0.103 kg). The density of densified briquettes was calculated using Equation (4) as follows:

$$D_B = \frac{M_S}{V_B} \quad (4)$$

where D_B is the density of the densified briquettes (m^3). The hardness of the densified briquettes was calculated using Equation (5) as follows:

$$H_D = \frac{F_C}{\delta_X} \quad (5)$$

where H_D is the hardness of densified briquettes (kN mm^{-1}), F_C is the compression force (N) and δ_X is the deformation of densified briquettes (mm). The pressure was calculated based on Equation (6) as follows:

$$P_R = \frac{F_C}{A_X} \quad (6)$$

where P_R is the pressure (MPa) and A_X is the area of pressing vessel (mm^2) defined in Equation (7) as follows:

$$A_X = \frac{\pi \cdot D^2}{4} \quad (7)$$

The numerical energy of the densified briquettes [27–29] was calculated using Equation (8) as follows:

$$E_N = \sum_{n=0}^{n=i-1} \left[\left(\frac{F_{n+1} + F_n}{2} \right) \cdot (x_{n+1} - x_n) \right] \quad (8)$$

where E_N is the numerical energy of the densified briquettes (J), $F_{n+1} + F_n$ and $x_{n+1} - x_n$ are the values of the compression force (N) and deformation (mm), n is the number of data points and i is the number of subsections of the deformation axis (-). The energy per unit volume of the densified briquettes was calculated using Equation (9) [30,31] as follows:

$$V_E = \frac{E_N}{V_B} \quad (9)$$

where V_E is the volume energy of the densified briquettes (m^3). The tangent curve model [26,32–34] was used to describe the theoretical dependency between the force and deformation curves of the densified briquettes, where the theoretical energy was determined. The tangent curve mathematical model is given in Equation (10) as follows:

$$F(X) = A \cdot (\tan(B \cdot X))^n \quad (10)$$

where F is the compression force (kN) and X is the deformation of the densified briquettes (mm), A is the force coefficient of mechanical behaviour (kN), B is the deformation coefficient of mechanical behaviour (mm^{-1}) and n is the value of the fitting function (-). The deformation X of each densified briquette was obtained from the plot of the force-deformation curve after the densification process. The coefficients A, B and n were determined using Mathcad 14 software based on the experimental relationship between the force and deformation curve. The use of the tangent curve model satisfies the boundary conditions of the densification test: zero compression force relates to zero deformation, compression force approaching infinity relates to limit deformation and integral of the tangent curve model relates to energy [26,32–34]. The data were analysed using the Mathcad software, version 14 and STATISTICA, version 13 [35,36].

3. Results

The amounts of deformation δ_X, thickness T_X, numerical energy E_N and theoretical energy E_T of densified briquettes of jatropha seedcake grouped by compression forces and samples dimensions are presented in Table 1, and graphically displayed in Figures 2–5, respectively.

The volume, density, hardness and volume energy of densified briquettes of jatropha seedcake at varying forces and dimensions are also given in Table 2.

Table 1. Dependent variables of the jatropha seedcake briquettes compaction at varying forces and dimensions (Mean ± Standard Deviation).

Force F_C (kN)	Dimensions D_m (mm)	Deformation δ_X (mm)	Thickness T_X (mm)	* Numerical Energy E_N (J)	** Theoretical Energy E_T (J)
100	4.5	29.79 ± 0.24	35.44 ± 0.34	455.28 ± 2.55	464.50 ± 24.76
	5.6	35.39 ± 2.50	35.35 ± 0.21	445.76 ± 12.45	485.1 ± 17.77
	6.7	33.24 ± 5.55	35.66 ± 1.19	433.46 ± 2.46	451.72 ± 22.76
	8	39.39 ± 3.35	35.75 ± 0.36	429.41 ± 5.81	471.87 ± 32.54
	10	29.08 ± 1.83	34.89 ± 0.16	398.8 ± 8.40	420.74 ± 0.45
200	4.5	39.45 ± 0.94	33.12 ± 0.54	897.70 ± 12.64	1074.67 ± 15.15
	5.6	39.18 ± 2.85	33.11 ± 0.56	886.53 ± 4.52	943.31 ± 92.11
	6.7	39.28 ± 2.98	33.22 ± 0.41	871.47 ± 5.54	1037.97 ± 43.12
	8	43.12 ± 1.91	33.12 ± 0.17	865.59 ± 19.25	975.69 ± 32.17
	10	34.38 ± 9.33	33.34 ± 1.64	851.28 ± 45.09	926.59 ± 101.63
300	4.5	41.09 ± 1.63	31,42 ± 0.11	1345.41 ± 9.25	1508.88 ± 20.66
	5.6	40.69 ± 4.86	30.99 ± 0.02	1315.45 ± 7.55	1456.07 ± 49.21
	6.7	40.71 ± 3.44	31.61 ± 0.66	1321.35 ± 15.87	1350.16 ± 21.43
	8	38.12 ± 4.56	31.31 ± 0.43	1297.63 ± 6.01	1477.62 ± 83.26
	10	37.23 ± 2.12	32.07 ± 2.03	1253.27 ± 75.74	1459.10 ± 40.56
400	4.5	43.33 ± 1.16	30.54 ± 0.06	1683.42 ± 4.47	1751.20 ± 44.29
	5.6	40.59 ± 5.58	30.70 ± 0.42	1657.82 ± 8.49	1894.03 ± 68.11
	6.7	39.17 ± 7.01	30.49 ± 0.01	1536.92 ± 73.51	1781.31 ± 38.34
	8	43.21 ± 8.14	30.64 ± 0.51	1640.81 ± 40.70	1738.05 ± 131.15
	10	44.64 ± 0.42	31.04 ± 0.65	1509.59 ± 79.26	1512.78 ± 68.39

* Equation (8), ** Equation (17).

Table 2. Volume, density and hardness of jatropha seedcake briquettes compaction at varying forces and dimensions (Mean ± Standard Deviation).

Force F_C (kN)	Dimensions D_m (mm)	*** Volume V_B (10^{-5} m^3)	*** Density D_B (kg m^{-3})	*** Hardness H_D (kN mm^{-1})	*** Volume Energy V_E (10^6 J m^{-3})
100	4.5	10 ± 0.10	1223 ± 10	3.36 ± 0.03	4.56 ± 0.05
	5.6	10 ± 0.10	1032 ± 73	2.83 ± 0.20	4.24 ± 0.03
	6.7	9.7 ± 0.30	1111 ± 19	3.05 ± 0.51	6.83 ± 3.87
	8	9.5 ± 0.00	928 ± 79	2.55 ± 0.22	9.28 ± 0.06
	10	9.5 ± 0.30	1255 ± 79	3.45 ± 0.22	9.24 ± 0.26
200	4.5	8.8 ± 0.10	924 ± 22	5.07 ± 0.12	14.99 ± 0.06
	5.6	8.9 ± 0.20	932 ± 68	5.12 ± 0.37	14.62 ± 0.12
	6.7	9.0 ± 0.60	930 ± 71	5.11 ± 0.39	16.68 ± 4.07
	8	8.7 ± 0.10	846 ± 37	4.64 ± 0.21	18.70 ± 0.39
	10	8.8 ± 0.10	1100 ± 31	6.04 ± 1.64	17.99 ± 0.57

Table 2. *Cont.*

Force F_C (kN)	Dimensions D_m (mm)	*** Volume V_B (10^{-5} m^3)	*** Density D_B (kg m^{-3})	*** Hardness H_D (kN mm^{-1})	*** Volume Energy V_E (10^6 J m^{-3})
300	4.5	10 ± 0.10	887 ± 35	7.31 ± 0.29	4.44 ± 0.07
	5.6	9.9 ± 0.10	902 ± 11	7.43 ± 0.89	4.31 ± 0.10
	6.7	9.5 ± 0.40	898 ± 76	7.40 ± 0.62	6.79 ± 3.96
	8	9.3 ± 0.00	963 ± 12	7.93 ± 0.95	9.47 ± 0.22
	10	9.2 ± 0.20	980 ± 56	8.07 ± 0.46	9.04 ± 0.04
400	4.5	8.8 ± 0.10	841 ± 23	9.24 ± 0.25	15.17 ± 0.12
	5.6	8.9 ± 0.10	906 ± 13	9.95 ± 1.37	14.83 ± 0.38
	6.7	8.7 ± 0.00	945 ± 17	10.38 ± 1.86	16.64 ± 3.95
	8	8.6 ± 0.00	858 ± 16	9.42 ± 1.78	18.22 ± 1.40
	10	8.6 ± 0.10	816 ± 80	8.96 ± 0.09	18.16 ± 1.90

*** Jatropha seedcake briquettes based on Equations (1), (4), (5) and (9).

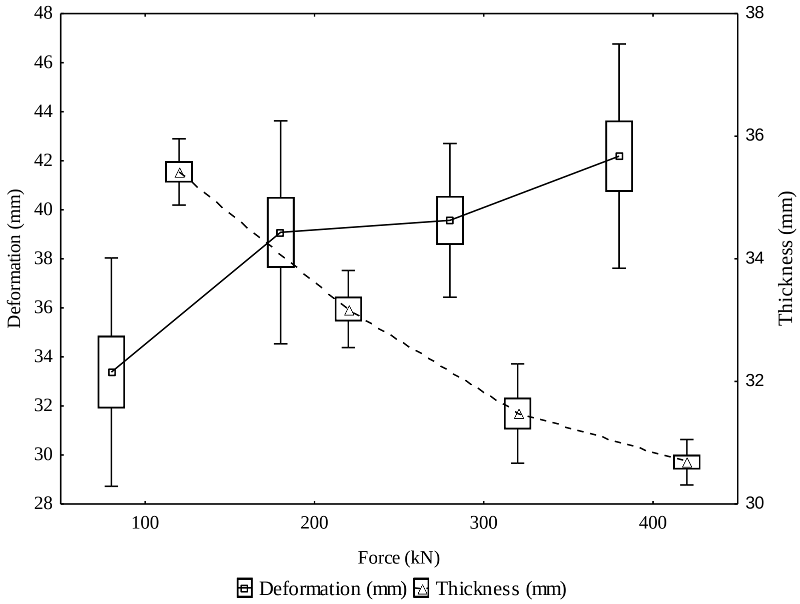

Figure 2. Box plot of deformation and thickness of samples grouped by force.

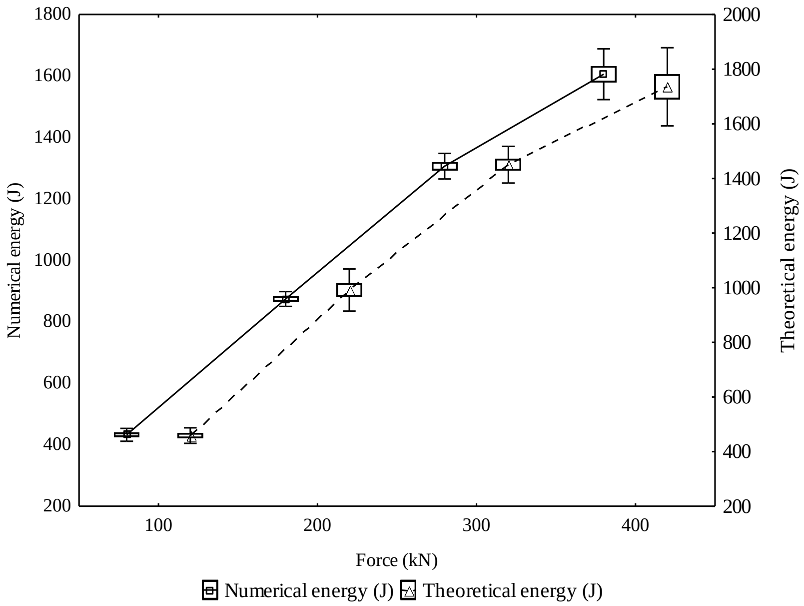

Figure 3. Box plot of numerical and theoretical deformation energy of samples grouped by force.

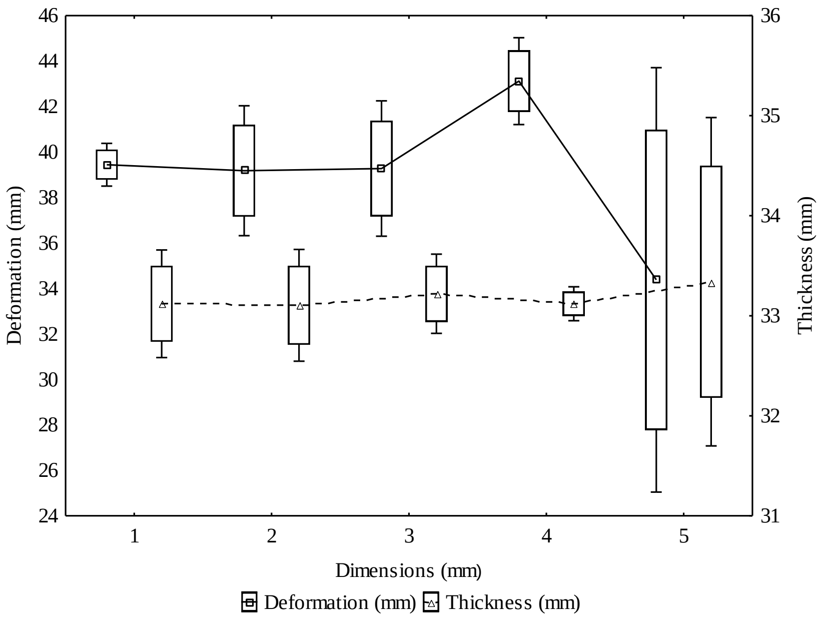

Figure 4. Box plot of deformation and thickness grouped by sample dimensions (1 = 4.5 mm; 2 = 5.6 mm; 3 = 6.7 mm; 4 = 8 mm and 5 = 10 mm) at force 200 kN, similar to forces 100, 300 and 400 kN.

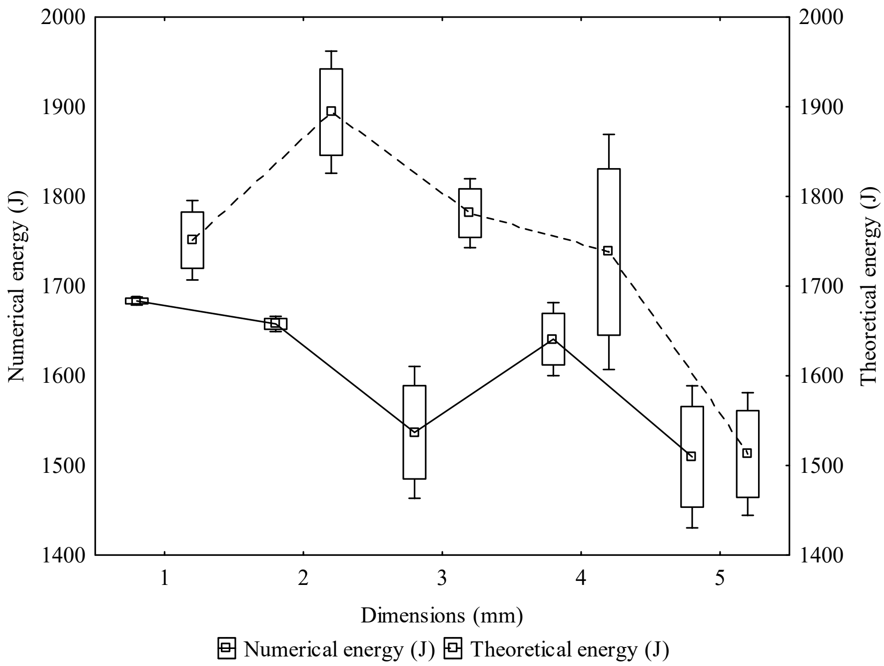

Figure 5. Box plot of numerical and theoretical energy grouped by sample dimensions (1 = 4.5 mm; 2 = 5.6 mm; 3 = 6.7 mm; 4 = 8 mm and 5 = 10 mm) at force 400 kN, similar to forces 100, 200 and 300 kN.

The multiple regression statistical results of the dependent variables of jatropha seedcake briquette compaction (deformation, thickness, numerical energy and theoretical energy) in relation to the effects of compression forces and samples dimensions are given in Tables 3 and 4.

Table 3. Multiple regression analysis of dependent variables in relation to the effect of compression forces and samples dimensions.

Dependent Variables	R^2 (-)	F-Ratio (-)	F-Critical (-)	*p*-Value (-)
Deformation δ_X (mm)	0.34	9.61	1.42	<0.05
Thickness T_X (mm)	0.87	127.99	1.42	<0.05
Numerical energy E_N (J)	0.99	1295.19	1.42	<0.05
Theoretical energy E_T (J)	0.96	443.35	1.42	<0.05

p-value < 0.05 or F-ratio > F-critical means statistically significant [36].

Table 4. Simple regression analysis of dependent variables in relation to the effect of compression forces.

Dependent Variables	R^2 (-)	F-Ratio (-)	F-Critical (-)	*p*-Value (-)
Deformation δ_X (mm)	0.34	19.43	1.60	<0.05
Thickness T_X (mm)	0.87	258.61	1.60	<0.05

p-value < 0.05 or F-ratio > F-critical means statistically significant [36].

The Analysis of variance (ANOVA) statistical results of the determined coefficients of the tangent curve model (Equation (10)) using Mathcad 14 software for a level of significance of 5% are given in Tables 5 and 6 respectively.

Table 5. Determined coefficients (A, B, n) and their statistical analysis for the calculation of the theoretical energy of jatropha seedcake briquettes at a forces 100 and 200 kN.

Force F_C (kN)	Dimensions D_m (mm)	A (kN)	B (mm^{-1})	n (-)	F-Ratio (-)	F-Critical (-)	P-Value (-)	R^2 (-)
100	4.5	1.01 ± 0.01	0.042 ± 0.001	2	0.008 ± 0.001	3.863 ± 0.007	0.927 ± 0.006	0.999 ± 0.001
	5.6	6.91 ± 1.41	0.038 ± 0.002		0.029 ± 0.009	3.866 ± 0.011	0.866 ± 0.023	0.998 ± 0.001
	6.7	7.96 ± 3.01	0.039 ± 0.004		0.024 ± 0.002	3.868 ± 0.004	0.878 ± 0.004	0.998 ± 0.001
	8	5.07 ± 1.03	0.035 ± 0.002		0.062 ± 0.027	3.867 ± 0.008	0.806 ± 0.041	0.996 ± 0.001
	10	8.54 ± 1.34	0.045 ± 0.002		0.033 ± 0.013	3.871 ± 0.011	0.859 ± 0.029	0.997 ± 0.001
200	4.5	11.16 ± 0.72	0.035 ± 0.001	2	0.072 ± 0.016	3.862 ± 0.007	0.789 ± 0.023	0.996 ± 0.001
	5.6	13.76 ± 5.22	0.037 ± 0.004		0.045 ± 0.009	3.868 ± 0.009	0.832 ± 0.018	0.997 ± 0.001
	6.7	9.72 ± 0.07	0.034 ± 0.001		0.093 ± 0.081	3.867 ± 0.012	0.775 ± 0.107	0.996 ± 0.001
	8	10.79 ± 4.16	0.034 ± 0.005		0.062 ± 0.008	3.865 ± 0.008	0.803 ± 0.013	0.995 ± 0.002
	10	11.84 ± 4.10	0.036 ± 0.004		0.064 ± 0.021	3.867 ± 0.007	0.801 ± 0.032	0.995 ± 0.001

A is the force coefficient of mechanical behaviour (kN), B is the deformation coefficient of mechanical behaviour (mm^{-1}), n is the fitting curve function exponent (-), F-ratio is the value of the F test (-), F-critical is the critical value that compares a pair of models (-), p value is the significance level used for testing a statistical hypothesis (-), R^2 is the coefficient of determination (-). *p*-value > 0.05 or F-critical > F-ratio means statistically significant [35].

Table 6. Determined coefficients (A, B, n) and their statistical analysis for the calculation of the theoretical energy of jatropha seedcake briquettes at a forces 300 and 400 kN.

Force F_C (kN)	Dimensions D_m (mm)	A (kN)	B (mm^{-1})	n (-)	F-Ratio (-)	F-Critical (-)	P-Value (-)	R^2 (-)
300	4.5	15.27 ± 0.38	0.033 ± 0.001	2	0.093 ± 0.057	3.864 ± 0.008	0.767 ± 0.074	0.995 ± 0.001
	5.6	15.33 ± 2.98	0.034 ± 0.004		0.077 ± 0.041	3.865 ± 0.011	0.786 ± 0.057	0.995 ± 0.001
	6.7	15.42 ± 1.40	0.033 ± 0.002		0.074 ± 0.053	3.866 ± 0.011	0.794 ± 0.077	0.996 ± 0.001
	8	17.52 ± 3.73	0.035 ± 0.003		0.060 ± 0.036	3.866 ± 0.005	0.811 ± 0.060	0.996 ± 0.001
	10	16.41 ± 0.33	0.036 ± 0.002		0.090 ± 0.051	3.866 ± 0.007	0.770 ± 0.066	0.995 ± 0.001
400	4.5	16.17 ± 0.61	0.031 ± 0.001	2	0.031 ± 0.003	3.875 ± 0.002	0.862 ± 0.006	0.998 ± 0.001
	5.6	18.65 ± 5.17	0.034 ± 0.004		0.050 ± 0.021	3.871 ± 0.004	0.826 ± 0.036	0.997 ± 0.001
	6.7	18.14 ± 8.73	0.036 ± 0.004		0.023 ± 0.007	3.872 ± 0.001	0.882 ± 0.021	0.9975 ± 0.001
	8	17.18 ± 6.05	0.032 ± 0.005		0.038 ± 0.002	3.868 ± 0.001	0.845 ± 0.005	0.997 ± 0.001
	10	12.05 ± 1.67	0.031 ± 0.001		0.045 ± 0.014	3.869 ± 0.005	0.833 ± 0.026	0.996 ± 0.001

A is the force coefficient of mechanical behaviour (kN), B is the deformation coefficient of mechanical behaviour (mm^{-1}), n is the fitting curve function exponent (-), F-ratio is the value of the F test (-), F-critical is the critical value that compares a pair of models (-), p value is the significance level used for testing a statistical hypothesis (-), R^2 is the coefficient of determination (-). *p*-value > 0.05 or F-critical > F-ratio means statistically significant [35].

The experimental and theoretical descriptions of the force and deformation curves of the densified briquettes of jatropha seedcake at a maximum force of 400 kN and a speed of 5 mm min^{-1} are shown in Figure 6. A similar description was observed for the compression forces of 100, 200 and 300 kN at the same speed for all experiments.

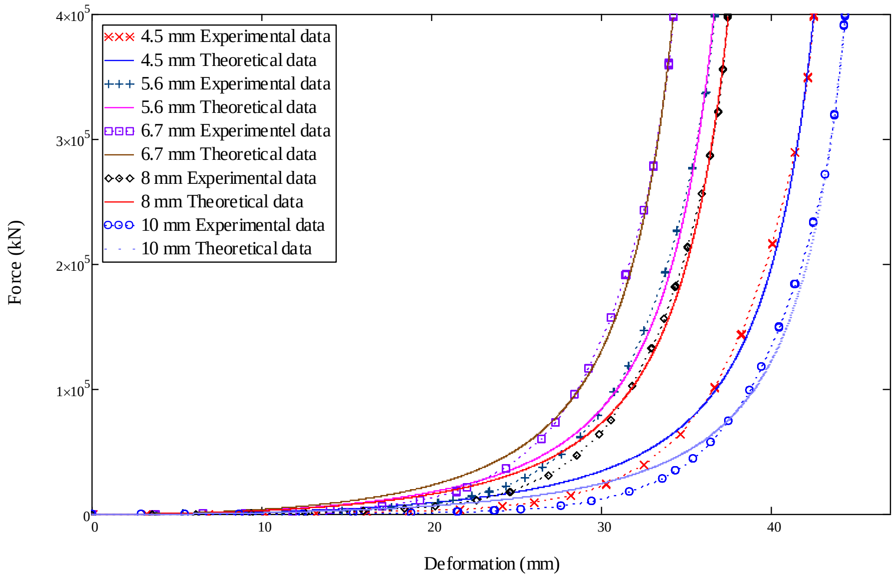

Figure 6. Description of force and deformation curves of experimental and theoretical data of densified jatropha seedcake briquettes of different dimensions at a maximum force of 400 kN and a speed of 5 mm min$^{-1.}$

4. Discussion

For the varying compression forces and sample dimensions, the deformation values ranged from 29.08 ± 1.83 to 44.64 ± 0.42 mm, thickness ranged from 30.49 ± 0.01 to 35.75 ± 0.36 mm, numerical energy ranged from 398.8 ± 8.40 to 1683.42 ± 4.47 J and theoretical energy ranged from 420.74 ± 0.45 to 1894.03 ± 68.11 J.

The volume of samples of bulk jatropha seedcake of different dimensions or size distributions as described in Equation (1) was calculated to be 16.9646×10^{-5} m^3. The mass of samples at an initial height of 60 mm was 0.103 kg, which remained constant in all the experiments. Here, the density of the samples was calculated to be 607.15 kg m^{-3}. The volume of densified briquettes varied with the dimensions of the sample, as described by Equation (2). The increase of compression forces decreased the density of densified briquettes while the hardness increased. There was no clear correlation between density, hardness and samples dimensions. The energy per unit volume of densified briquettes and compression forces also showed no correlation in comparison with the dimensions of the sample that indicated a positive linear correlation.

The results of the multiple regression statistical analysis were statistically significant (*p*-value < 0.05 or F-ratio > F-critical) [36]. This means that the independent variables (compression forces and samples dimensions) had a significant effect on the dependent variables (deformation, thickness, numerical energy and theoretical energy). The general linear models of the dependent variables are described in Equations (11)–(14). The coefficients of determination (R^2) were 0.34, 0.87, 0.99 and 0.96 respectively.

$$\delta_X = 32.48 + 0.03 \cdot F_C - 0.22 \cdot D_m \quad (11)$$

$$T_X = 36.49 - 0.02 \cdot F_C + 0.06 \cdot D_m \quad (12)$$

$$E_N = 127.68 + 3.95 \cdot F_C - 20.25 \cdot D_m \tag{13}$$

$$E_T = 167.52 + 4.29 \cdot F_C - 26.88 \cdot D_m \tag{14}$$

Based on the statistical analysis results, it is important to note that the model coefficients of the compression forces were significant (p-value < 0.05) for all the dependent variables. Similarly, the coefficients of the dimensions of the sample were significant but only for the numerical and theoretical energies. The deformation and thickness coefficients were not significant (p-value > 0.05) [36] in relation to the dimensions of the sample. This means that there was no significant correlation between samples dimensions and dependent variables namely deformation δ_X and thickness T_x. Therefore, Equations (11) and (12) were modified as given in Equations (15) and (16) using the simple linear regression where the compression force F_C was considered as the continuous regressor.

$$\delta_X = 31.83 + 0.03 \cdot F_C \tag{15}$$

$$T_X = 36.67 - 0.02 \cdot F_C \tag{16}$$

The ANOVA statistical results of the determined coefficients of the tangent curve model (Equation (10)) using the Mathcad 14 software for a level of significance of 5% were significant, that is, the values of F-critical were greater than the F-ratio values or the p-values were greater than the probability level of 0.05 [35]. This indicates that the tangent curve model is suitable for fitting the experimental dependency between force and deformation curves of bulk agricultural materials and/or products under compression loading [32–34]. The determined amounts of the force coefficient of mechanical behaviour A for all compression forces F_C and samples dimensions D_m ranged between 5.07 ± 1.032 and 18.14 ± 8.73 kN, while that of the deformation coefficient of mechanical behaviour B ranged between 0.031 ± 0.001 and 0.045 ± 0.002 mm^{-1}. The fitting function exponent n of the tangent model was found to be 2 (-).

The numerical energy, Equation (8) [27,28,32], is the area under the force and deformation curve [31,37]. It was theoretically determined by integrating Equation (10) for n = 2 (-), which produced Equation (17) as follows:

$$F(X) = A \cdot (\tan(B \cdot X))^{n=2} \rightarrow \frac{A \cdot (\tan(B \cdot X) - B \cdot X)}{B} \tag{17}$$

The application of Equation (17) requires that the theoretical description of the experimental dependency between force and deformation curves, that is, the force coefficient of mechanical behaviour A (kN), the deformation coefficient of mechanical behaviour B (mm^{-1}) and the fitting function exponent n (-) must be determined using Equation (10). To emphasize more the numerical energy of the densified briquettes, it was seen that the increase in densified briquettes dimensions or size distributions decreased the energy. This suggests that the sample dimension of 10 mm could be economically viable for briquette energy sources. However, for assessing the quality of biomass briquettes with respect to energy demand, it is necessary to examine the physical properties such as the durability, compressive strength, calorific value, moisture content and binders for briquette formation. The study results are part of the comprehensive knowledge required for designing optimal technology for producing solid biofuels biomass briquettes as a renewable energy resource.

5. Conclusions

The increase in compaction forces increased the hardness of the jatropha seedcake briquettes. Compaction forces had a significant effect on briquettes deformation and thickness, while the dimensions of the sample did not. The increase in samples dimensions decreased the briquettes' compaction energy. Sample dimensions of 4.5 mm recorded the highest energy, compared to those of the 10 mm, which had the lowest. The determined coefficients of the tangent curve mathematical model theoretically described the experimental data, that is, the dependency between the force and deformation curves of the jatropha seedcake briquettes at different dimensions and forces.

Supplementary Materials: The following are available online at http://www.mdpi.com/1996-1073/11/8/1980/s1.

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