Mitchual *et al. International Journal of Energy and Environmental Engineering* 2013, 4:30
http://www.journal-ijeee.com/content/4/1/30

International Journal of
Energy and Environmental Engineering
a SpringerOpen Journal

ORIGINAL RESEARCH Open Access

Effect of species, particle size and compacting pressure on relaxed density and compressive strength of fuel briquettes

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Abstract

Densification of biomass waste materials has provided a great boost to the utilization of wood and agricultural waste for domestic and industrial fuel. However, the processes involved in the production of this fuel make it more expensive than fossil fuel. This is because densification of wood waste into fuel briquettes is not simple. This paper reports the results of research conducted to determine the effect of species, particle size and compacting pressure on relaxed density and compressive strength in cleft of briquettes produced from sawdust of tropical hardwoods. Briquettes were made using a laboratory hydraulic press. Compacting pressure was varied from 10 to 50 MPa at an interval of 10 MPa. Species used were *Triplochiton scleroxylon*, *Ceiba pentandra*, *Aningeria robusta*, *Terminalia superba*, *Celtis mildbreadii* and *Piptadenia africana*. The results indicate that species, compacting pressure and particle size of sawdust at 5% level of significance have significant effect on the relaxed density and compressive strength in cleft of briquettes produced. The multiple correlation coefficient (*R*) and adjusted R^2 for the regression model between relaxed density of briquettes, and species density, particle size and compacting pressure were 0.93 and 0.87, respectively. Additionally, the multiple correlation coefficient and adjusted R^2 for the regression model between compressive strength of briquettes, and species density, particle size and compacting pressure were 0.83 and 0.69, respectively. The regression models suggest that species density, particle size and compacting pressure are good predictors of relaxed density and compressive strength in cleft of briquettes produced from sawdust of tropical hardwoods.

Keywords: Briquette; Species; Compacting pressure; Particle size; Relaxed density; Compressive strength

Background

Renewable source of energy is the fastest growing source of world energy, with consumption increasing by 3% per year [1]. This is due to its environmental friendliness as against the rising concern about the environmental impact of fossil fuel use and also strong government incentives for increasing renewable penetration in most countries around the world [1]. Globally, biomass currently provides around 46 EJ of bioenergy in the form of combustible biomass and wastes, liquid biofuels, solid biomass/charcoal and gaseous fuels. This share is estimated to be over 10% of global primary energy, with over two-thirds consumed in developing countries as traditional biomass for household use [2]. Previous studies conducted to examine the economic impacts of using biomass energy clearly show that the benefits of production of briquettes for many economies clearly exist. However, there are several important factors that limit their utilization. The main reason is the high production cost resulting from high energy input in the production of various bioenergy fuel. From the past to the present, various scientists have carried out studies that have led to the improvement and better understanding of the technology for production of biomass briquettes. For example, it has been reported that pre-heating the biomass raw materials before pressing could reduce the power requirement for pressing of briquettes [3]. In a study conducted to improve biomass briquetting, it was observed that an average electrical energy saving at the heater, motor and overall system were 23.5%, 10.8% and 10.2%, respectively. This was achieved

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when the biomass raw material was heated before pressing [3]. Other studies suggest that blending of two biomass raw materials could improve the durability characteristics of briquettes produced [4]. Material and process variables that could additionally influence the physical and mechanical characteristics of briquettes are compacting pressure, moisture content, particle size distribution of biomass raw material and temperature. According to [5], briquettes manufactured at lower pressures (30 to 60 MPa) fall to pieces easily. However, briquettes produced at higher pressures (150 to 250 MPa) are consistent and compact. Furthermore, the density and durability (mechanical strength) of briquettes are inversely proportional to the particle size since smaller particles have greater surface area during densification [6]. In this paper, the researchers investigated the effect of species, particle size and compacting pressure on relaxed density and compressive strength in cleft of fuel briquettes made at room temperature using low compacting pressure.

Methods

Materials and material preparation

Sawdust from the following selected tropical hardwood species were used for the study: *Triplochiton scleroxylon*, *Ceiba pentandra*, *Aningeria robusta*, *Terminalia superba*, *Celtis mildbreadii* and *Piptadenia africana*. These species were classified into lower density (*T. scleroxylon* and *C. pentandra*), medium density (*A. robusta* and *T. superba*) and high density (*C. mildbreadii* and *P. africana*). The sawdust was sun-dried at an average relative humidity and temperature of 75% and 28°C, respectively, between 5 and 7 days. Thereafter, the sawdust of each species was classified into particle size (PS): PS ≤ 1 mm, 1 mm < PS ≤ 2 mm and 2 mm < PS ≤ 3.35 mm using an automatic sieve shaker with serial number A060-01/ZG/0038 and model A060-01.

Moisture content

The moisture content, on oven-dry basis, of the sawdust was determined in accordance with [7]. A sample of 2 g of sawdust of each species was weighed and placed in a laboratory oven at a temperature of 103°C and dried until the difference in mass between two successive weighing, separated by an interval of 2 h, was 0.01 g or less. The moisture content of the specimen was then computed as follows:

$$Moisture\ content = \frac{M_1 - M_o}{M_o} \times 100, \tag{1}$$

where M_1 and M_o are mass of test samples before drying and when oven-dried, respectively (g).

Density of species

Density of the six timber species from which sawdust was collected and determined was in accordance with [8]. Fifteen clear specimens with dimensions of 20 mm × 20 mm × 30 mm were prepared for each species. The oven-dried masses of the specimens were determined. Thereafter, they were dipped one by one in paraffin wax and then kept in a desiccator. The volume displacement method which employs the use of Eureka can and a measuring cylinder was used to determine the volumes of the specimen. The density of each specimen was then computed as:

$$Density = \frac{Mass\ of\ specimen}{Volume\ of\ specimen}. \tag{2}$$

Briquetting process

A 55.3-mm ID × 52.5-cm height cylindrical mould was used to produce the briquettes. Ninety grammes of sawdust of each species and particle size was weighed and filled into the mould. The average moisture content of the sawdust was 11.46%. A manual hydraulic press with a gauge and a piston was used to compress the raw material without a binder against the other end of the mould to form the briquettes. A clearance of about 0.1 mm was provided between the piston and the inner wall of the mould to allow for air escape. The samples were pressed using the following predetermined compacting pressure levels: 10, 20, 30, 40 and 50 MPa. The dwelling time for each press was maintained at 10 s for all the pressing made. This process was repeated for all the six species and particle size.

Physical and mechanical properties of briquettes

The relaxed density and compressive strength in cleft of the briquettes were investigated using standard testing methods.

Relaxed density

Relaxed density of the briquettes was determined 30 days after removal from the press in accordance with [9]. The mass of the briquettes was determined using a laboratory electronic balance with an accuracy of 0.01 g. The diameter and length of the briquette were measured at three points with a digital vernier calliper. Relaxed density (RD) was then computed as:

$$RD\ (g/cm^3) = \frac{108000 \times M(g)}{\pi[d_1(mm) + d_2(mm) + d_3(mm)]^2 \times [l_1(mm) + l_2(mm) + l_3(mm)]} \tag{3}$$

where d_1, d_2 and d_3 were diameters of briquettes at points one, two and three, respectively, measured in millimetres; l_1, l_2 and l_3 were lengths of briquettes at points one, two and three, respectively, measured in millimetres. M is the mass of briquette in grammes.

Compressive strength

Compressive strength in cleft of briquettes was determined in accordance with [10] using an Instron Universal Strength (Norwood, MA, USA) testing machine with load cell capacity of 100 kN. The cross-head speed was 0.305 mm/min. A sample of briquette to be tested was placed horizontally in the compression test fixture and a load was applied at a constant rate of 0.305 mm/min until the briquette failed by cracking. The compressive strength in cleft was then computed as follows:

$$\text{Compressive strength in cleft } (N/mm) = \frac{3 \times \textit{The load at fracture point } (N)}{[l_1(mm) + l_2(mm) + l_3(mm)]} \qquad (4)$$

where l_1, l_2 and l_3 were lengths of briquettes at points one, two and three, respectively (mm).

Results and discussion

Relaxed density

The result in Table 1 (particle size < 1 mm) indicates that the relaxed density of briquettes made from *C. pentandra*, the species with the lowest density (409 kg/m^3), ranged from 398 to 716 kg/m^3, while that of *C. mildbreadii*, species with the highest density (764 kg/m^3) ranged from 453 to 706 kg/m^3. The lowest relaxed density for all the briquettes produced from particle size < 1 mm was 366 kg/m^3 (*T. scleroxylon* at compacting pressure = 10 MPa), and the highest was 741 kg/m^3 (*P. africana* at compacting pressure = 50 MPa). The result in Table 2 for 1 mm ≤ particle size < 2 mm also shows that the relaxed density of briquettes made from *C. pentandra* ranged from 386 to 692 kg/m^3, whilst that of *C. mildbreadii* ranged from 435 to 658 kg/m^3. The result also indicates that the lowest relaxed density for 1 mm ≤ particle size < 2 mm was 354 kg/m^3 (*T. scleroxylon* at compacting pressure = 10 MPa), and the highest was 723 kg/m^3 (*P. africana* at compacting pressure = 50 MPa). Considering Table 3 which indicates the relaxed density for 2 mm ≤ particle size < 3.35 mm, it shows that briquettes made from *C. pentandra* had relaxed density ranging from 373 to 651 kg/m^3, whilst that of *C. mildbreadii* ranged from 430 to 655 kg/m^3. Additionally, the lowest relaxed density for this particle size was 324 kg/m^3 (*T. scleroxylon* at compacting pressure = 10 MPa), and the highest was 720 kg/m^3 (*P. africana* at compacting pressure = 50 MPa). Briquettes' relaxed densities obtained from this study were consistent with suggestions by [6] that briquettes made from hydraulic piston press are usually less than 1,000 kg/m^3 and are usually between 300 and 600 kg/m^3 in density [11]. Correlation analysis between relaxed density on one hand and compacting pressure and particle size on the other hand indicates that there was a weak significant negative correlation between relaxed density and particle size of briquettes produced (Pearson's $r = -0.188$, p value = 0.000; $N = 450$; one-tailed, $\alpha = 0.05$). Compacting pressure was also found to have a very strong positive significant correlation with the relaxed density of the briquettes produced (Pearson's $r = 0.901$, p value = 0.000; $N = 450$; one-tailed, $\alpha = 0.05$). These results suggest that the relaxed density of the briquettes produced increases with increasing compacting pressure level and that briquettes produced from sawdust of tropical hardwoods species with smaller particle size are likely to have higher relaxed density than those with larger particle size. This result confirms that of other researchers [2,12]. It is reported that in reality, in briquetting, when a large

Table 1 Relaxed density (kg/m^3) of briquettes made from six tropical hardwood species (PS < 1 mm)

Species	Compacting pressure				
	10 MPa	20 MPa	30 MPa	40 MPa	50 MPa
C. pentandra	398	523	622	666	716
T. scleroxylon	366	458	545	594	632
A. robusta	440	543	607	636	695
T. superba	447	557	631	675	727
P. africana	465	567	637	679	741
C. mildbreadii	453	533	611	662	706

Table 2 Relaxed density (kg/m^3) of briquettes made from tropical hardwood species (1 mm ≤ PS < 2 mm)

Species	Compacting pressure				
	10 MPa	20 MPa	30 MPa	40 MPa	50 MPa
C. pentandra	386	503	606	646	692
T. scleroxylon	354	452	535	591	627
A. robusta	362	466	538	586	658
T. superba	437	548	615	651	680
P. africana	441	534	610	664	723
C. mildbreadii	435	491	562	621	658

Table 3 Relaxed density (kg/m^3) of briquettes made from tropical hardwood species (2 mm ≤ PS < 3.35 mm)

Species	Compacting pressure				
	10 MPa	20 MPa	30 MPa	40 MPa	50 MPa
C. pentandra	373	489	598	618	651
T. scleroxylon	324	435	508	552	597
A. robusta	345	463	519	571	573
T. superba	396	514	591	649	673
P. africana	417	530	604	658	720
C. mildbreadii	430	487	543	612	655

proportion of the raw material is of smaller particles, the briquette produced will have a higher density [2,12]. The reason for this trend is that increasing the compacting pressure will lead to the particles of biomass material being closely packed due to reduction of void ratio and plastic deformation of the sawdust particles, therefore leading to increased density of the briquettes [13]. Additionally, if the raw material is finer, it gives a larger surface area for bonding which results in the production of briquette with higher density. Table 4 which shows the analysis of variance (ANOVA) of the relaxed density of briquettes produced indicates that at 5% level of significance, species, particle size, compacting pressure and their interactions have significant effects on the relaxed density of briquettes produced. The multiple coefficient of determination value and the root mean square error for the ANOVA model were 0.9907 and 11.24, respectively. Thus, it could be deduced that species, particle size and compacting pressure, and their interactions explained about 99.07% of the variability in the relaxed density of the briquettes produced.

Multiple linear regression analysis to establish the relative contribution of species density, particle size and compacting pressure in the prediction of the relaxed density of briquette and the mathematical relationship between the dependent variable relaxed density and the independent variables, species density, particle size and compacting pressure, is indicated in Table 5. The result (Table 5) shows the unstandardized (β) and standardized (Beta) regression coefficients, the multiple correlation coefficient (R), adjusted R^2, the value of t and its associated p value for each of the variables. As shown in Table 5, species density, particle size and compacting pressure collectively explained 87.1% (adjusted R^2 = 0.871) of the variance in the relaxed density of briquette produced. This suggests that the linear regression model is a good predictor of briquettes' relaxed density (R^2 = 0.872, p value = 0.000).

Table 4 ANOVA of effect of biomass material, PS and compacting pressure on relaxed density of briquettes

Source	*df*	ANOVA SS	Mean square	*F* ratio	*p* value
Species	5	452,443.680	90,488.736	715.19	< 0.0001[a]
Particle size	2	174,914.253	87,457.127	691.23	< 0.0001[a]
CP	4	4,106,254.742	1,026,563.686	8113.63	< 0.0001[a]
Species × CP	20	45,562.164	2,278.108	18.01	< 0.0001[a]
Species × Particle size	10	38,280.947	3,828.095	30.26	< 0.0001[a]
Particle size × CP	8	3,449.324	431.166	3.41	0.0009[a]
Species × Particle size × CP	40	22,406.809	560.170	4.43	< 0.0001[a]
Error	360	45,548.400	126.523		

df degree of freedom, *CP* compacting pressure. [a]Statistically significant at 0.05 level of significance.

Table 5 Regression of relaxed density of briquettes on species density, particle size compacting pressure of briquettes

Variables	β	Beta	R	Adjusted R^2	t	p value
Constant	334.651		0.934	0.871	34.238	0.000
Species density	0.125	0.160			9.446	0.000
Particle size	−23.997	−0.188			−11.109	0.000
Compacting pressure	6.639	0.901			53.234	0.000

Additionally, based upon the Beta values, it could be deduced that compacting pressure explained the bulk of the variance in the relaxed density of the briquette produced (Beta = 0.901, t = 53.234, p value = 0.000) and was the best predictor of relaxed density of the briquette. However, species density and particle size of sawdust used significantly contributed to the model (species density: Beta = 0.160, t = 9.446, p value = 0.000; particle size: Beta = −0.188, t = −11.109, p value = 0.000). Furthermore, it could be deduced from the β values that the mathematical relationship between the dependent variable Relaxed density and the independent variables, namely species density (S), PS and compacting pressure (CP) is

$$\text{Relaxed density}\ \left(\text{kg/m}^3\right) = 334.651 + 0.125\text{S}–23.997\text{PS} + 6.639\text{CP}. \tag{5}$$

Compressive strength in cleft

Briquettes' compressive strength is one of the indices used to assess its ability to be handled, packed and transported without breaking. Tables 6, 7 and 8 indicate the compressive strength in cleft of the briquette produced. The result for particle size < 1 mm (Table 6) indicates that at all compacting pressure levels, the compressive strength in cleft of *C. pentandra*, was exceptionally high compared to that of the other species. Compressive strength in cleft of *C. pentandra* ranged from 15.81 to 44.58 N/mm for compacting pressure levels 10 to 50 MPa. *C. mildbreadii* comparatively had the lowest compressive

Table 6 Compressive strength (N/mm) in cleft of briquettes made from tropical hardwood species (PS < 1 mm)

Species	Compacting pressure				
	10 MPa	20 MPa	30 MPa	40 MPa	50 MPa
C. pentandra	15.81	29.23	39.26	40.40	44.58
T. scleroxylon	3.33	9.35	14.27	20.66	30.56
A. robusta	3.97	8.23	16.28	19.48	26.63
T. superba	2.13	6.16	10.44	13.64	18.92
P. africana	1.76	5.95	10.13	17.06	21.14
C. mildbreadii	1.30	3.55	6.69	10.51	12.45

Table 7 Compressive strength (N/mm) in cleft of briquettes made from tropical hardwood species (1 mm ≤ PS < 2 mm)

Species	Compacting pressure				
	10 MPa	20 MPa	30 MPa	40 MPa	50 MPa
C. pentandra	7.28	24.34	34.74	42.62	52.60
T. scleroxylon	6.97	14.66	27.53	36.57	38.31
A. robusta	3.47	9.51	14.42	21.62	27.50
T. superba	3.26	6.61	12.50	14.89	18.03
P. africana	2.60	6.99	12.65	17.80	24.05
C. mildbreadii	2.59	5.64	9.63	12.49	16.40

strength in cleft, ranging from 1.30 to 12.45 N/mm for the same compacting pressure levels. The result for 1 mm ≤ particle size < 2 mm (Table 7) and 2 mm ≤ particle size < 3.35 mm (Table 8) reflected the trend for particle size < 1 mm. In both cases, the compressive strength in cleft of *C. pentandra* was exceptionally higher than that of the other species. Correlation analysis indicated a weak significant positive correlation between particle size and compressive strength in cleft (Pearson's $r = 0.179$, p value = 0.000; $N = 450$; one-tailed, $\alpha = 0.05$), that is, as particle size increased the compressive strength in cleft of briquettes produced also increased. This result contradicts the assertion by [2,6] and [12] that, in general, the durability (mechanical strength) of pellets are inversely proportional to particle size since smaller particles have greater surface area for moisture addition during steam conditioning therefore resulting in increased starch gelatinization and better binding. The reason for the deviation is that, in this study, the briquettes were formed at low temperature (i.e. room temperature); thus, the formation of solid bridge resulting from the natural bonding of chemicals may be absent or minimal.

Therefore, the major contributing factors to the bond formed during this densification may be the mechanical interlock of the fibres of the biomass and adhesive force between the particles. Increase in fibre length of the biomass raw material resulting from increased particle size could lead to mechanical interlocking of relatively longer fibres [14] which, therefore, result in the formation of a stronger bond and increased compressive strength in cleft. Additionally, a strong significant positive correlation between compressive strength in cleft and compacting pressure of briquettes produced was established (Pearson's r = 0.670, p-value = 0.000; N = 450; 1-tailed, α = 0.05). This result means that the compressive strength in cleft of the briquettes produced increased with increasing compacting pressure. Increased compacting pressure result in increased binding force between the particles [13]. The increase in binding force resulted from increased mechanical interlocking of sawdust particle as well as increased adhesion between the particles [6].

Table 8 Compressive strength (N/mm) in cleft of briquettes made from tropical hardwood species (2 mm ≤ PS < 3.35 mm)

Species	Compacting pressure				
	10 MPa	20 MPa	30 MPa	40 MPa	50 MPa
C. pentandra	13.80	26.71	36.73	45.40	51.45
T. scleroxylon	6.98	15.24	27.64	36.86	40.89
A. robusta	2.69	11.90	17.29	21.35	26.88
T. superba	4.22	9.58	13.05	15.80	24.67
P. africana	3.97	15.28	24.24	41.83	55.45
C. mildbreadii	3.62	5.78	10.18	12.66	19.18

Table 9 ANOVA of effect of biomass material, PS and CP on compressive strength in cleft of briquettes

Source	*df*	ANOVA SS	Mean square	*F* ratio	*p* value
Species	5	29,475.439	5,895.088	1,316.33	< 0.0001[a]
Particle size	2	2,688.496	1,344.248	300.16	< 0.0001[a]
CP	4	36,597.173	9,149.293	2,042.97	< 0.0001[a]
Species × CP	20	4,451.833	222.592	49.70	< 0.0001[a]
Species × Particle size	10	3,592.241	359.224	80.21	< 0.0001[a]
Particle size × CP	8	902.633	112.829	25.19	< 0.0001[a]
Species × Particle size × CP	40	2,186.188	54.655	12.20	< 0.0001[a]
Error	360	1,612.234	4.47843		

df degree of freedom, *CP* compacting pressure. [a]Statistically significant at 0.05 level of significance.

The ANOVA of compressive strength in cleft of briquettes produced (Table 9) indicates that at 5% level of significance, compacting pressure, species, particle size and their interactions had significant effects on the compressive strength in cleft of the briquettes produced (p value < 0.05). The multiple coefficient of determination value and root mean square error for the ANOVA model were 0.9802 and 2.1162, respectively. It could therefore be deduced that the species type of the biomass raw material, its particle size and compacting pressure could explain about 98.02% of the variability in the compressive strength in cleft of the briquettes produced. The summary of the result of linear multiple regression to establish the relative contribution

Table 10 Regression of compressive strength in cleft of briquettes on species density, particle size and compacting pressure

Variables	β	Beta	R	Adjusted R^2	t	p value
Constant	19.923		0.829	0.685	10.081	0.000
Species density	−0.046	−0.454			−17.147	0.000
Particle size	2.957	0.179			6.770	0.000
Compacting pressure	0.637	0.670			25.267	0.000

of species density, particle size and compacting pressure towards the prediction of compressive strength in cleft of the briquette and the mathematical relationship between the dependent variable compressive strength in cleft and independent variables, species density, particle size and compacting pressure, is as indicated in Table 10. Table 10 also indicates the β and Beta regression coefficients, R, adjusted R^2, the value of t and its associated p values for each of the variables.

The result indicates that species density, particle size and compacting pressure collectively explained 68.5% (adjusted R^2 = 0.685) of the variance in the compressive strength in cleft of the briquette produced. This suggests that the regression model is a good predictor of compressive strength in cleft of the briquettes produced (R^2 = 0.685, p value = 0.000).

The Beta value for the three predictive variables suggests that compacting pressure explained the bulk of the variance in the compressive strength in cleft of the briquette produced (Beta = 0.670, t = 25.267, p value = 0.000) and was the best predictor of compressive strength in cleft of the briquette produced. That notwithstanding, species density and particle size of sawdust used significantly contributed to the regression model (species density: Beta = −0.454, t = −17.147, p value = 0.000; particle size: Beta = 0.179, t = 6.770, p value = 0.000). The values of β also suggest that the mathematical relationship between compressive strength in cleft of briquettes produced and S, PS and CP is

$$\begin{aligned}&\text{Compressive strength in cleft (N/mm)}\\&\quad = 19.923\text{–}0.046\text{S} + 2.957\text{PS} + 0.637\text{CP}.\end{aligned} \tag{6}$$

Conclusions

This study examined the effect of species, particle size and compacting pressure on relaxed density and compressive strength of fuel briquettes. From the study, it could be concluded that (1) briquettes with adequate compressive strength in cleft could be produced from *C. pentandra* at room temperature using compacting pressure as low as 20 MPa; (2) the type of species, compacting pressure and particle size as well as their interactions have a significant effect on the relaxed density and compressive strength in cleft of briquettes produced from sawdust of *T. scleroxylon*, *C. pentandra*, *A. robusta*, *T. superba*, *C. mildbreadii* and *P. africana*; (3) the mathematical relationship between RD of briquette and species density, particle size and compacting pressure is as follows: Relaxed density = 334.651 + 0.125S − 23.997PS + 6.639CP; and (4) the mathematical relationship between compressive strength in cleft and species density, particle size and compacting pressure is as follows: Compressive strength in cleft = 19.923 − 0.046S + 2.957PS + 0.637CP. This study provides a better understanding of some of the factors that influence production of briquettes from sawdust of tropical hardwood species.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

SJM conceived the study, participated in the design of the study, drafted the manuscript and participated in the sequence alignment. KFM participated in the design of the study and sequence alignment. NAD participated in the design of the study, performed the statistical analysis and participated in the sequence alignment. All authors read and approved the final manuscript.

Acknowledgements

The authors are grateful to the Civil Engineering Department of Kwame Nkrumah University of Science and Technology and Forest Research Institution of Ghana for providing laboratory support for this study. Special thanks also go to Miss Agnes Ankomah of Crop Research Institute of Ghana for providing statistical software for this research work.

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Received: 24 February 2013 Accepted: 10 July 2013
Published: 14 Aug 2013

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doi:10.1186/2251-6832-4-30
Cite this article as: Mitchual *et al.*: **Effect of species, particle size and compacting pressure on relaxed density and compressive strength of fuel briquettes.** *International Journal of Energy and Environmental Engineering* 2013, 4:30