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Original scientific paper

# Characterisation of Coconut Coir Under Compaction: Determination of Pellet Density, Specific Energy and Compression Force

Juan LIU, Yudi LIU, Zhuoyu YAN, Mingze XU, Zhixu WANG, Dezhi REN, Xuewei BAI*, Dejun LIU

**Abstract:** Coconut coir dust has a potential utilization as bio-fuel pellet. The objective of this contribution is to understand the mechanical characterisation of coconut coir under compaction. Four moulds with hole diameter of 6, 12, 20 and 25 mm are adopted in producing coconut coir pellet. Data of unit pellet density, compression force and specific energy are analyzed with specific hole diameter, mould thickness, and ratio of compacted pellet height. It is observed that unit pellet densities are larger than 1,0 g/cm$^3$ for hole diameter range from 6 to 12 mm except the ratio of compacted pellet height 2,5 of hole diameter 6 mm The specific energy required is 11,2 - 13,6 J/g while unit pellet density is compacted to approximate 0,7 g/cm$^3$ the compression force goes increasingly as the plunger is moving ahead, and to the maximal value at the end of stroke in close-end mode, while in open-end mode, the peak compression force presents gradual decreasing, increasing and stable trend as the compression stroke continues over time. The Pearson correlation analysis indicated that the maximum compression force in close-end mode has little influence on the stable compression force in open-end.

**Keywords:** coconut coir dust; compression force; pellet density; specific energy

## 1 INTRODUCTION

In many coconut-producing region, Sri Lanka, India, Philippines, Indonesia, Mexico, Costa Rica, and Guyana, a small amount of coconut coir dust was used for making bio-compost and most of the coir dust was left as an unwanted by-product [1]. Though this crop biomass waste is also a renewable and abundant organic resource, the efficient use of crop waste was limited by technical constraints and by the intrinsic characteristics of the sources, such as relatively low density and morphological diversification. The pretreatment of the crop waste is the challenging issue in the intensive agricultural area [2, 3].

Densification of bulky biomass material into solid pellet is a low-cost and environmental-friendly option in utilization of some agricultural by product. The bulk density significantly increased by about 9 to 12 fold after the pelleting process; pelletization on its own has proven benefits on energy densification, in terms of volume reduction with uniform-sized shape for long-distance transportation and storage [5, 6].

One of the most influential variables in pellet production is the type of biomass, which will ultimately regulate the physical properties (i.e., bulk density, unit pellet density, and durability) of pellets [7]. Castellano and co-workers analyzed the physical quality of the pellets made from nine different kinds of raw biomass and found that the composition and structure of the raw materials determine their agglomeration potential. In addition to this, the type of biomass affects the pressure and power demand in pelletization, mechanical durability of the pellets [8]. Saha et al. investigated the feasibility of producing briquettes from coconut coir dust and rice husk blends without binder. They found that mixing ratio had a significant effect on the physical, mechanical and combustion properties of pellets [9]. The particularities of different biomass make it necessary to adapt the pelletization process to produce pellets that fulfills the quality requirements.

Except the nature of agricultural biomass, moisture content of raw material, the degree of fragmentation and the working parameters of the compacting machine all influence physical properties of the pellets [10]. To design the workable pelleting process, comprehensive knowledge of the relationship between process variables and pellet physical properties is necessary. It is evident that the optimum process conditions for pelletization is different for each individual feedstock [11]. Samuelsson reported that moisture content was the dominant factor for bulk density, which is explained by the alteration of the friction through the mould due to the lubricating property of water [12]. Mani et al. reported that particle size distribution has an effect on pellet quality [13]. Kaliyan et al. claimed that finely ground biomass tended to give more durable pellets than the coarsely ground biomass [14]. However, Tabilet al. (1996) observed the trend of an increase in alfalfa pellet durability when using a larger hammer mill screen [15]. Mohsenin and Zaske reported that greater displacement hold-time results in a greater decay of stress causes expansion after the compaction pressure is released [16]. Tumuluru et al. found that pelleting woody biomass at high-moisture content of 33% helps to reduce drying cost, and the specific energy consumption is < 116 kWh/t at die speed of 60 Hz, and preheating temperature of 90 °C [17].

Design parameters of the mould, for example the diameter and the thickness, play a major role on both the quality of the biomass pellet and mechanical behaviour [18]. Crawford et al. studied the pressure $P_P$ required to compress loose biomass into a densified pellet [19], and it can be given by:

$$P_P = P_C \cdot e^{4\mu_w \cdot \kappa \cdot L/D} \tag{1}$$

where $P_C$ is the pressure required to compress the loose biomass to the desired pellet density, $\mu_w$ is the coefficient of friction between the mould wall and the biomass plug, $\kappa$ is the radial-to-axial stress proportionality constant, $L$ and $D$ is length and diameter of the mould.

The relation of compressive force/pressure and density was especially of great interests. It helps to select the appropriate motor for pelleting machines, and provides basic constraints for assessing the mechanical properties of working part using computer-aided engineering analysis tools [20].

Jones [21] represented the density-pressure relation in the form of Eq. (2).

$$\ln(\rho) = m \cdot \ln(P) + b \quad (2)$$

where, $\rho$ is the bulk density of the material compacted, kg/m$^3$; $P$ is the applied compressive pressure, MPa; $m$ and $b$ are model constants that are determined from the slope and intercept, respectively.

Li proposed [22] the density-pressure data of compacted biomass material with open-end mode in the form of Eq. (3).

$$P = A \cdot e^{B \cdot (1 - \rho_0 / \rho)} \quad (3)$$

where, $P$ is the compressive force, N; $\rho_0$ is the initial density of feedstock, kg/m$^3$; $\rho$ is the density in compression, kg/m$^3$, and $A$, $B$ are model constants related to the type of biomass and processing parameters. It is shown that higher feeding amount of biomass feedstock (alfalfa, wheat straw and chinensis were utilized in their research) produces large value of $A$ but small value of $B$.

In this research, coco coir dust is used as experimental material, densification is conducted with the biomass compression setup, unit pellet density and specific energy are investigated regarding processing variables: mould diameter, thickness and ratio of length-to-diameter. Furthermore, the mechanical behavior is also the main concern in this study; the feature of compression force on displacement and time is explored under both close-end and open-end compression mode.

## 2 MATERIALS AND METHODS

### 2.1 Raw Material Preparation

Coconut coir is chopped and then ground using a mill (WILEY Laboratory Mill Model 4, ARTHUR H. THOMAS COMPANY). Fig. 1 shows the raw material and some pellets with different diameters produced in trials. The moisture content of raw coconut coir is lower than 10% with wet basis [23], water is sprayed onto the raw material after grounding to get the appropriate moisture content for making pellets. The samples are packed into water-tight bags after being evenly sprayed with purified water, then the biomass material was mixed manually for every 8 h to obtain a full absorption of water and homogeneity. The wetted samples are stored in a container at 10 °C - 15 °C for 48 h prior to testing. The raw material moisture content is adjusted to 15% ± 0,2% (w.b.), and the bulk density of the material is 307 ± 2,2 kg/m$^3$. In this study, we tried to maintain the same level of moisture content and bulk density of the sample raw material in compaction process. To evaluate the coconut coir dust particle distribution, sieve analysis is conducted in accordance with ANSI/ASAE S424.1 [24]; the cumulative percent mass distribution undersize of material is listed in Tab. 1. It illustrates that more than 90% in mass of raw material's nominal particle size is smaller than 0,36 mm; the coir dust is fully mixed to ensure the even distribution of particle in process.


**Figure 1** Raw material of coconut coir, and pellets produced

**Table 1** Cumulative percent mass distribution undersize of coconut coir dust

| Screen No. | 20 | 30 | 40 | 45 | 50 | 60 | pan |
|---|---|---|---|---|---|---|---|
| nominal size opening / mm | 0,85 | 0,60 | 0,43 | 0,36 | 0,30 | 0,25 | 0 |
| Mass undersize percentage / % | 100,0 | 99,0 | 98,9 | 91,7 | 86,3 | 67,0 | 49,4 |

### 2.2 Compression Mode

Four sets of biomass unheated compaction setup, as shown in Fig. 2, are adopted in the experiment. It consists of mould, compressing plunger, two supports, and block bar.

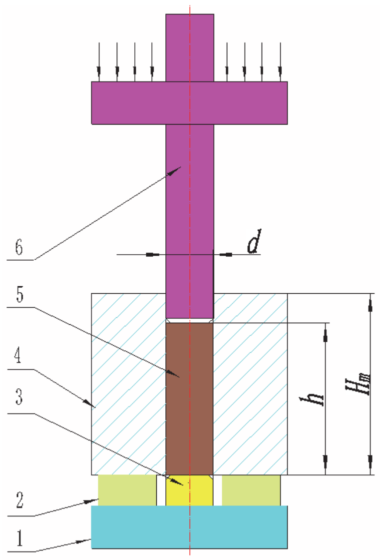



**Figure 2** Biomass compression setup
1. bottom plate, 2. mould support, 3. block bar, 4. mould, 5. coconut coir dust, 6. compressing plunger

Two types of compression modes are defined in this study, namely, close-end and open-end mode, according to the installation of block bar or not. For the closed-end mode, the block bar is fitted inside the outlet of the mould hole while compressing the biomass; the blocked biomass material then is compacted in a close chamber. This mode corresponds to the pre-filling of material in production of biomass pellets, it is an essential step to establish the necessary pelleting condition. For open-end compression mode, the supports will be released after several strokes of close-end compression mode. This mode corresponds to the continuous working condition in biomass pellet production. The compression tests are performed with a universal testing machine (MTS Systems Corporation, Type: Criterion Model 45) where the compression force is measured with a MTS force transducer with the maximal force of 100 kN, and the compressing displacements are recorded simultaneously.

### 2.3 Pelleting Process Variables

Some variables related to pelleting process are illustrated in Fig. 2, mould diameter *d*, mould thickness $H_m$, and $R_{hd}$, which is defined by the ratio of compacted pellet height *h* to *d. T*hese process variables influence the pellet physical properties like density, specific energy consumed and mechanical properties like compression force required [19]. Four moulds are designed with diameters *d*, which range from 6 mm to 25 mm, and thickness $H_m$, which ranges from 23 mm to 90 mm. The ratio $R_{hd}$ is obtained by configuring the compress displacement *h* for the given mould. Pelleting process variables in the experiment were listed in column 1 - 3 of Tab. 2.

### 2.4 Density of Unit Pellet and Mechanical Properties

In this work, the pellets compacted in stable stage of open-end mode are sealed immediately in water-tight bags. After a week's storing in a cabinet with approximate room temperature of 18 °C, the diameter and height of pellets are measured with a caliper with 0.02 mm resolution, and the average value of 5 measurements in different direction is used for each sample; the mass of each pellet sample is weighed with an electronic balance (0.01 g resolution, model ML4002E/03, Mettler-Toledo International Inc.). The average density of unit pellet *dp* is calculated by dividing the mass by the volume of individual pellets.

The compressive force in the experiment is recorded with the load sensor (model 661.20E-03, MTS Systems Corporation) of the universal testing machine, and the sampling rate is 5 samples/s.

Specific energy *W* is defined as the energy consumed to produce unit mass of pellet [25]. In this work, the specific energy is calculated through integration of the force-displacement curve using the trapezoidal rule.

## 3 RESULTS AND DISCUSSION

### 3.1 Effect of Mould Diameter, Ratio $R_{hd}$ on Unit Pellet Density and Specific Energy

It is important to know the relationship between the mould dimension parameters and final density of pellets, the mould diameter and the ratio of length-to-diameter. These factors significantly affect the amount of material that can be pelleted [26]. In addition, a knowledge of the force and specific energy consumed for compression is significant to determine power requirements [27].

The dimension of the mould *d*, $H_m$ used in the experiment, ratio $R_{hd}$ and unit pellet density, the maximal force $f_{C\max}$ of stroke in close-end, and force $f_{O\max}$ in open-end mode as well as specific energy *W* are presented in Tab. 2.

**Table 2** Coconut dust pellet characteristics under close- and open-end conditions

| *d* / mm | $H_m$ / mm | $R_{hd}$ | $d_p$ / g/cm$^3$ | $f_{C\max}$ / N | $f_{O\max}$ / N | *W* / J/g |
|---|---|---|---|---|---|---|
| 6 | 23 | 2,17 | 1,40 | 9774 | 7001,5 | 77,8 |
| 6 | 23 | 2,50 | 0,39 | 209 | 79,9 | 4,9 |
| 6 | 23 | 2,83 | 1,13 | 2602 | 12412,6 | 173 |
| 6 | 23 | 3,17 | 1,30 | 960 | 20594,2 | 356,3 |
| 12 | 51 | 2,17 | 1,25 | 62987 | 11027,4 | 21,3 |
| 12 | 51 | 2,58 | 1,29 | 7509 | 18466,4 | 40,4 |
| 12 | 51 | 3,00 | 1,02 | 1007 | 6348,3 | 19,4 |
| 12 | 51 | 3,42 | 1,18 | 102 | 26172,8 | 76,4 |
| 12 | 51 | 3,83 | 1,10 | 83 | 7538,7 | 48,2 |
| 20 | 76 | 1,80 | 0,38 | 19241 | 223,0 | 0,8 |
| 20 | 76 | 2,30 | 0,93 | 4787 | 28068,8 | 19,0 |
| 20 | 76 | 2,80 | 0,7 | 701 | 10900,3 | 11,2 |
| 20 | 76 | 3,30 | 0,63 | 117 | 5138,3 | 8,29 |
| 20 | 76 | 3,40 | 0,7 | 122 | 5427,9 | 13,6 |
| 25 | 90 | 2,16 | 0,35 | 3841 | 212,2 | 0,5 |
| 25 | 90 | 2,56 | 0,52 | 1663 | 1430,7 | 1,9 |
| 25 | 90 | 2,96 | 0,93 | 312 | 9382,0 | 7,4 |
| 25 | 90 | 3,20 | 0,45 | 112 | 529,6 | 1,0 |

The maximum unit pellet density $d_p$ of 1,4 g/cm$^3$ is at mould diameter *d* of 6 mm with ratio 2,17, while for *d* of 12, 20, and 25 mm, the maximum density is 1,29, 0,93 and 0,93 g/cm$^3$ respectively; the ratio at the peak values is at the range from 2,3 to 2,96; the maximum density tends to decrease with the larger diameter in general, as shown in Fig. 3. Unit pellet densities are larger than 1,0 g/cm$^3$ for *d* of 6 mm and 12 mm except the pellet compacted at ratio 2,5 with *d* of 6 mm. In our previous work, we found that the pellet density decreased by the increasing diameter with single-factor experiment [22]. The same conclusion was reached regarding the relationship between diameter and density by Rahaman et al. [28].

Theerarattananoon et al. studied the influence of pelleting variables on density of biomass pellets. They found that mould thickness had a positive effect on true density of the pellet [29]. In this work, for the given diameter, a larger ratio $R_{hd}$ actually implicates a larger thickness according to its definition; the effect of $R_{hd}$ or thickness of mould on density is not positive at some cases. That may be caused by the difference in raw material and the ratio value in numerical range.

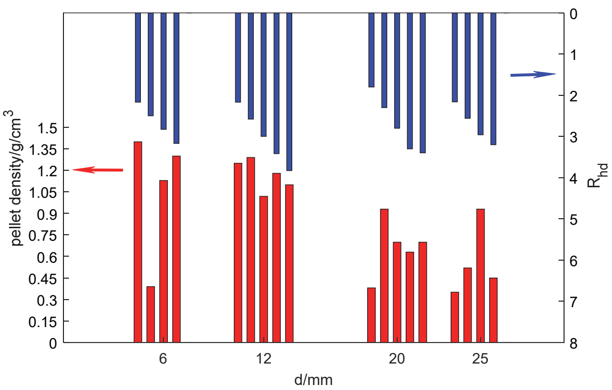



**Figure 3** Pellet density versus mould diameter at different ration $R_{hd}$

The specific energy for coconut coir dust in pelleting varies greatly with different mould diameter as shown in Fig. 4 and the maximum $W$ is 356,3 J/g that occurs with mould diameter of 6 mm; actually in the pelleting experiment, the pellet produced is blocked in the chamber under these circumstances, it does not go ahead toward the outlet continuously even in open-end compression mode. Sudden ejects of hard pellet happen after several compacting strokes, in fact, it corresponds to an abnormal working situation. The specific energy in pelleting coir dust with mould diameter 12 mm is in the range of 20 - 80 J/g, while the pellet density range is from 1,0 g/cm$^3$ to 1,3 g/cm$^3$. The ratio $R_{hd}$ played a vital role to attain the qualified pellet density, when ratio varies from 1,8 to 3,4 using moulds with diameter of 12 mm and 25 mm, specific energy is less than 20 J/g, and the maximum pellet density of 0,93 g/cm$^3$. O'dogherty reported that the specific energy for parallel-sided moulds was up to 40 MJ/t (40 J/g) to achieve densities about 700 kg/m$^3$(0,7 g/cm$^3$) that depends on the mould form [30]. In our work, when the coir dust pellet density is compacted to approximately 700 kg/m$^3$(0,7 g/cm$^3$), the specific energy required is 11,2 - 13,6 J/g.

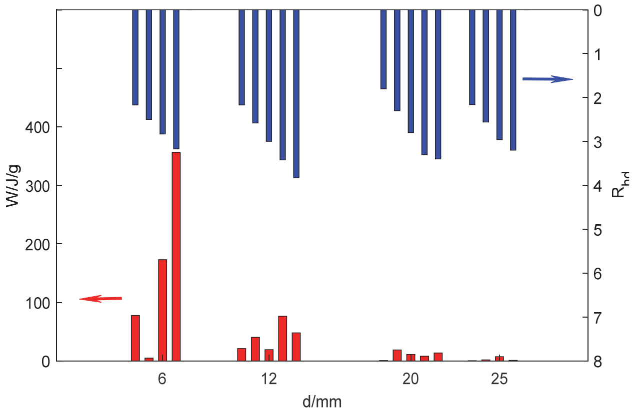


**Figure 4** Specific energy versus mould diameter at different ratio $R_{hd}$

### 3.2 The Mechanical Behaviors of Close-and Open-end Mode

In compression coconut coir dust, we found some basic and general mechanical characteristics. It indicated that the compression force behaved in complex ways when loaded, and exhibited time-dependent, force-deformation characteristics.

#### 3.2.1 The Compression Force on Displacement in One Stroke

The compressing force varies distinctively under same displacement but in different compression mode. As shown in Fig. 5, we take the compression force data with displacement. In close-end mode, the force goes increasingly as the plunger is moving ahead, and to the maximal value at the end of stroke, and the force difference between two successive strokes in compacted phase was getting bigger, as illustrated in Fig. 3 by the third stroke in the close-end mode.

With respect to the close-end mode, the maximal compression force did not appear at the end of pushing displacement for open-end mode Three stages are discovered to represent different moving and densifying state of biomass material. Firstly, the pellet being compacted in previous strokes stayed in the mould, which provided the supporting force for compressing the low-density bulky biomass into high-density pellet; with the advance of compressing plunger, the biomass material became denser and denser, until the compression force reached the maximum static friction between stayed pellet and inner wall of mould, the compression force also arrived at its peak value; secondly, a sudden drop of compression force appeared along with the starting of synchronous movement of new compacted and previous pellet in the mould; thirdly, with the compressive plunger going ahead, part of pellet is being extruded out of the mould, the compression force, its magnitude now is equal to the sliding friction between pellet and inner wall of the mould, usually in a relatively stable range in one stroke.

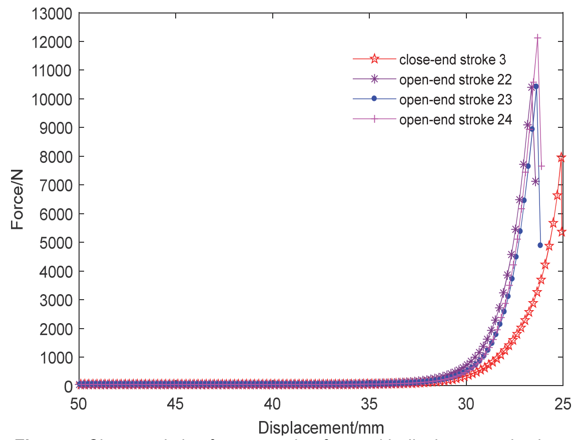


**Figure 5** Characteristic of compressing force with displacement in close-end and open-end mode, the mould diameter is 12 mm, and the stroke is 25 mm from start point at 50 mm to end point at 25 mm

#### 3.2.2 The Characteristic of Compression Force with Time in Close-end Mode

Fig. 6 shows the compression force in 12 strokes upon time in pelleting the coconut coir dust in close-end mode, the peak value and the corresponding time in each stroke are selected. It is found that an exponential function can be used to represent the relationship of maximal force to time, the force-time data and the fitting line are illustrated in Fig. 6, the coefficient of determination is 0,9959, which indicates that the fitting model satisfies high accuracy requirement. In other compression tests in close-end mode, the similar force-time behaviors are also examined.

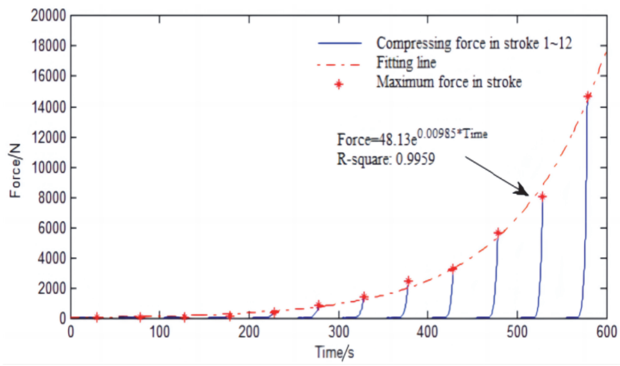
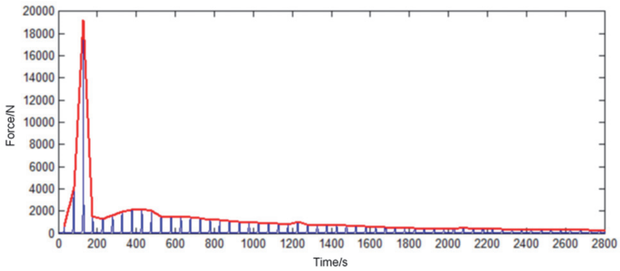


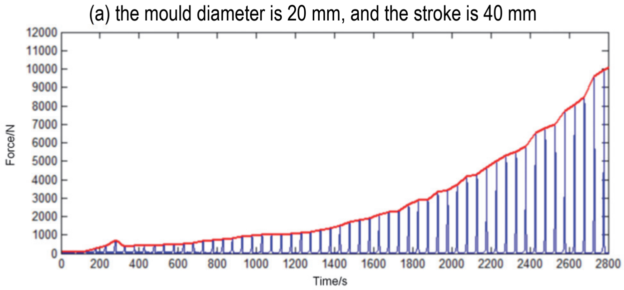
**Figure 6** Compression force with time in close-end mode, the mould diameter is 6 mm, and the stroke is 8 mm

### 3.2.3 The Characteristic of Compression Force with Time from Close-end Mode to Open-end

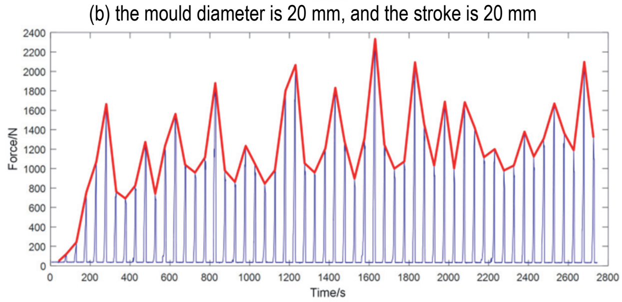
The compression force in the whole pelleting process for every treatment in the experiment is logged, including 5 strokes of close-end mode in the beginning, and all the force data in open-end mode in pelleting experiment. Three types of plot are given according to the trend of compression force to time. The maximum force appears with an exponential growth with time for close-end mode; after 5 strokes, the block of the biomass compression setup is released, the pelleting process is then in open-end mode. In some cases, the maximal compression force of each stroke decreases gradually over time. At last the feeding biomass is pushed directly through the mould in bulk and loose form, the force characteristic is shown in Fig. 7a. This case is in line with some cases of pelleting in engineering, the inappropriate structural parameters (such as mould diameter, thickness in this research) of the pelleter will lead to failure in work. Other cases that should be avoided in engineering are shown in Fig. 7b; the compression force maintains continuous increasing trend over time, the tests in this situation are frequently with raspy noises and violent vibration, which may cause the damage to mechanical part or electric motor in engineering.




(a) the mould diameter is 20 mm, and the stroke is 40 mm




(b) the mould diameter is 20 mm, and the stroke is 20 mm




(c) the mould diameter is 25 mm, and the stroke is 26 mm

**Figure 7** The typical compression force over time

In the test of compressing coconut coir dust with mould diameter 6 mm, ratio $R_{hd}$ 3,17, the peak force with close-end mode after 5 strokes is 960,4 N, then it increases to 20594,2 N in average with open-end mode compression, and the specific energy reaches 356,25 J/g with density of 1,13 g/cm$^3$. The similar average density (1,10 g/cm$^3$) of pellet made with mould diameter 12 mm and ratio $R_{hd}$ 3,83, the specific energy is 48,18 J/g, and the corresponding peak force is 7538,7 N.

Fig. 7c shows the feasible compression force characteristics in pelleting with stable running conditions. The coir dust is compacted with mould diameter 25 mm. The compression force still increases gradually after 5 strokes in close-end pelleting; it takes about 30 strokes to enter stable phase in open-end mode. Then the peak force is about 13,00 N in every stroke, and varies in a small range, which is capable of densifying loose biomass into high-density pellet. The density of pellet produced in the stable phase is 0,52 g/cm$^3$ in this test.

### 3.3 Pearson Correlations Analysis of Maximum Force in Close-end on Pellet Density Produced in Open-end Mode

The Pearson correlation analysis of the maximum compression force $f_{C\max}$ in close-end mode on the maximum compression force $f_{O\max}$ in steady phase with open-end mode is studied; also the correlation of pellet density $dp$ and compression force of both close-and open-end mode are investigated, as shown in Tab. 3. For biomass material, the force $f_{O\max}$ in steady stage is not related to both $f_{C\max}$ in initial stage and the pellet density $dp$, whereas correlation coefficient for $dp$ and $f_{O\max}$ is significant at the 0,01 level for coconut coir material. The close relation between density and pressure is verified by many studies: Wongsiriamnuay and Tippayawong reported that increase in the compression pressure resulted in an increase in relaxed density [31], Guo et al. also reported that the compact density of biomass increased with increasing pressure [32].

By observing in the experiment, the $f_{C\max}$ in close-end mode has short-term effect on the compression force in open-end mode. It usually takes some strokes to reach a new magnitude of compression force. The force $f_{O\max}$ in steady stage with open-end mode is insignificantly influenced by $f_{C\max}$ at the start of pelleting in long-term effect. The unit pellet density is greatly determined by the force $f_{O\max}$ in steady stage with open-end mode.

**Table 3** The Pearson correlation analysis of maximum compression force in close- and open-end mode and pellet density

| | | $f_{C\max}$ | $f_{O\max}$ | $d_p$ |
|---|---|---|---|---|
| $f_{C\max}$ | Pearson Correlation | 1,000 | 0,085 | 0,343 |
| | Sig. (2-tailed) | | 0,738 | 0,163 |
| $f_{O\max}$ | Pearson Correlation | 0,085 | 1,000 | 0,673 |
| | Sig. (2-tailed) | 0,738 | | 0,002 |
| $d_p$ | Pearson Correlation | 0,343 | 0,673 | 1,000 |
| | Sig. (2-tailed) | 0,163 | 0,002 | |

## 4 CONCLUSION

The experimental results showed that there is a significant effect of the mould diameter, and ratio of length to diameter on the pellet density and specific energy in pelleting coconut coir dust. The compression force behaves differently under close-end and open-end mode, the compression force is in continuous growth in one-stroke with close-end mode, while in open-end mode, the compression force decreases after an initial increase.

Three working conditions corresponding to engineering pelletization can be observed regarding force characteristics over time. The Pearson correlation analysis indicates that the maximum compression force in close-end mode has little influence on the stable compression force in open-end. The unit pellet density produced in open-end mode is mainly related to the maximum force of each stroke in open-end mode.

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## 5 REFERENCES

[1] Hamidul Islam, M., Mosharraf Hossain, M., & Abdul Momin, M. (2014). Development of Briquette from Coir Dust and Rice Husk Blend: An Alternative Energy Source. *International J. of Renewable Energy Development, 3*(2), 119-123. https://doi.org/10.14710/ijred.3.2.119-123

[2] Kumar, P., Subbarao, P. M. V., Kala, L., & Kumar Vijay, V. (2022). Influence of physical, mechanical, and thermal properties of biomass pellets from agriculture residue: pearl millet cob and mix. *Bioresource Technology Reports*, *20*, 101278. https://doi.org/10.1016/j.biteb.2022.101278

[3] Valdés, C. F., Chejne, F., Marrugo, G. P., Gómez, C. A., Marin-Jaramillo, A., & Norena-Marin, L. (2017). Energy evaluation of pelletized mixtures of iwtp sludge and coal-fired boiler ashes by co-combustion: identification of synergistic effects. *Applied Thermal Engineering*, *124*, 191-201. https://doi.org/10.1016/j.applthermaleng.2017.06.007

[4] Bergström, D., Israelsson, S., Öhman, M., Dahlqvist, S., Gref, R., Boman, C., & Wästerlund, I. (2008). Effects of raw material particle size distribution on the characteristics of Scots pine sawdust fuel pellets *Fuel Processing Technology, 89*(12), 1324–1329. https://doi.org/10.1016/j.fuproc.2008.06.001

[5] Jackson, J., Turner, A., Mark, T., & Montross, M. (2016). Densification of biomass using a pilot scale flat ring roller pellet mill. *Fuel Processing Technology, 148,* 43-49. https://doi.org/10.1016/j.fuproc.2016.02.024

[6] Valdes, C. F., Marrugo, G. P., Chejne, F., Marin-Jaramillo, A., Franco-Ocampo, J., & Norena-Marin, J. (2020). Co-gasification and co-combustion of industrial solid waste mixtures and their implications on environmental emissions, as an alternative management. *Waste Management, 101,* 54-65. https://doi.org/10.1016/j.wasman.2019.09.037

[7] Angulo-Mosquera, L. S., Alvarado-Alvarado, A. A., Rivas-Arrieta, M. J., Cattaneo, C. R., Rene, E. R., & García-Depraect, O. (2021). Production of solid biofuels from organic waste in developing countries: a review from sustainability and economic feasibility perspectives. *Science of The Total Environment, 95*(11), 1448816. https://doi.org/10.1016/j.scitotenv.2021.148816

[8] Castellano, J. M., Gómez, M., Fernández, M., Esteban, L. S., & Carrasco, J. E. (2015). Study on the effects of raw materials composition and pelletization conditions on the quality and properties of pellets obtained from different woody and non woody biomasses. *Fuel, 139*, 629-636. https://doi.org/10.1016/j.fuel.2014.09.033

[9] Saha, K. K., Hossain, M. M., Ali, M. R., & Alam, M. M. (2016). Feasibility study of coconut coir dust briquette. *Journal of the Bangladesh Agricultural University, 12*(2), 369-376. https://doi.org/10.3329/jbau.v12i2.28697

[10] Mišljenović, N., Čolović, R., Vukmirović, Đ., Brlek, T., & Bringas, C. S. (2016). The effects of sugar beet molasses on wheat straw pelleting and pellet quality. A comparative study of pelleting by using a single pellet press and a pilot-scale pellet press. *Fuel Processing Technology, 144*, 220-229. https://doi.org/10.1016/j.fuproc.2016.01.001

[11] Niedziółka, I., Szpryngiel, M., Kachel-Jakubowska, M., Kraszkiewicz, A., Zawiślak, K., Sobczak, P., & Nadulski, R. (2015). Assessment of the energetic and mechanical properties of pellets produced from agricultural biomass. *Renewable Energy,* 76, 312-317. https://doi.org/10.1016/j.renene.2014.11.040

[12] Samuelsson, R., Larsson, S. H., Thyrel, M., & Lestander, T. A. (2012). Moisture content and storage time influence the binding mechanisms in biofuel wood pellets. *Applied Energy, 99*, 109-115. https://doi.org/10.1016/j.apenergy.2012.05.004

[13] Mani, S., Tabil, L. G., & Sokhansanj, S. (2003). An overview of compaction of biomass grinds. *Powder Handling & Processing, 15*(2), 160-168.

[14] Kaliyan, N. & Morey, R. V. (2009). Factors affecting strength and durability of densified biomass products. *Biomass and Bioenergy, 33*(3), 337-359. https://doi.org/10.1016/j.biombioe.2008.08.005

[15] Tabil, L. G., Ghazanfari, A., Shaw, M., Opoku, A., & Whistlecraft, J. (2006). Disinfestation of timothy hay bales from hessian fly (mayetiola destructor (say)) puparia using high compression re-baling machines. *Canadian Biosystems Engineering, 48*, 3.47–3.51.

[16] Mohsenin, N. & Zaske, J. (1976). Stress relaxation and energy requirements in compaction of unconsolidated materials. *Journal of Agricultural Engineering Research, 21*(2), 193-205. https://doi.org/10.1016/0021-8634(76)90074-3

[17] Tumuluru, J. S. (2016). Specific energy consumption and quality of wood pellets produced using high-moisture lodgepole pine grind in a flat die pellet mill. *Chemical Engineering Research and Design, 110*, 82-97. https://doi.org/10.1016/j.cherd.2016.04.007

[18] Garcia-Maraver, A., Rodriguez, M. L., Serrano-Bernardo, F., Diaz, L. F., & Zamorano, M. (2015). Factors affecting the quality of pellets made from residual biomass of olive trees. *Fuel Processing Technology, 129,* 1-7. https://doi.org/10.1016/j.fuproc.2014.08.018

[19] Crawford, N. C., Ray, A. E., Yancey, N. A., & Nagle, N. (2015). Evaluating the pelletization of "pure" and blended lignocellulosic biomass feedstocks. *Fuel Processing Technology, 140*, 46-56. https://doi.org/10.1016/j.fuproc.2015.08.023

[20] Bai, X. W. (2014). Process Parameters Optimization and Mechanical Simulation in Densification of Corn Stalk Powder. *Shenyang Agricultural University.*

[21] Jones, W. (1960). Fundamental principles of powder metallurgy. *London: Edward Arnold Publishers Ltd*

[22] Li, X. Y., Yang M. S., & Tong, S. M. (1997). The Effect of Charge Die on Compression Proeess of Baler. *Journal of Inner Mongolia Institute of Agriculture & Animal Husbandary, 18*(1), 66–69

[23] American Society of Agricultural and Biological Engineers. (2021). *Moisture Measurement-Forages.* (ANSI/ASAE S358.3).

[24] American Society of Agricultural and Biological Engineers. (2017). *Method of Determining and Expressing Particle Size of Chopped Forage Materials by Screening.* (ANSI/ASAE S424.1 MAR1992).

[25] Mani, S., Tabil, L. G., & Sokhansanj, S. (2006). Specific energy requirement for compacting corn stover. *Bioresource Technology, 97*(12), 1420-1426. https://doi.org/10.1016/j.biortech.2005.06.019

[26] Ishii, K. & Furuichi, T. (2014). Influence of moisture content, particle size and forming temperature on productivity and quality of rice straw pellets. *Waste Management, 34*(12), 2621-2626. https://doi.org/10.1016/j.wasman.2014.08.008

[27] Tumuluru, J. S., Conner, C. C., Hoover, A. N. (2016). Method to produce durable pellets at lower energy consumption using high moisture corn stover and a corn starch binder in a flat die pellet mill. *Journal of Visualized Experiments, 112*, e54092. https://doi.org/10.3791/54092

[28] Rahaman, S. A. & Salam, P. A. (2017). Characterization of cold densified rice straw briquettes and the potential use of sawdust as binder. *Fuel Processing Technology, 158*, 9-19. https://doi.org/10.1016/j.fuproc.2016.12.008

[29] Theerarattananoon, K., Xu, F., Wilson, J., Staggenborg, S., Mckinney, L., Vadlani, P., Pei, Z., & Wang, D. (2011). Effects of the pelleting conditions on chemical composition and sugar yield of corn stover, big bluestem, wheat straw, and sorghum stalk pellets. *Bioprocess and Biosystems Engineering, 35*(4), 615-623. https://doi.org/10.1007/s00449-011-0642-8

[30] O'Dogherty, M. J. (1989). A review of the mechanical behaviour of straw when compressed to high densities. *Journal of Agricultural Engineering Research, 44*, 241-265. https://doi.org/10.1016/s0021-8634(89)80086-1

[31] Wongsiriamnuay, T. & Tippayawong, N. (2015). Effect of densification parameters on the properties of maize residue pellets. *Biosystems Engineering, 139*, 111-120. https://doi.org/10.1016/j.biosystemseng.2015.08.009

[32] Guo, L., Wang, D., Tabil, L. G., & Wang, G. (2016). Compression and relaxation properties of selected biomass for briquetting. *Biosystems Engineering, 148*, 101-110. https://doi.org/10.1016/j.biosystemseng.2016.05.009

**Contact information:**

**Juan LIU,** Assciate professor, PhD
School of Civil Engineering, Liaoning Petrochemical University,
No. 1, West Dandong Road, Wanghua District, Fushun, Liaoning Province, P.R.C.
E-mail: liujuan@lnpu.edu.cn

**Yudi LIU,** postgraduater student
Shenyang Agricultural University,
No. 120 Dongling Road, Shenhe District, Shenyang, Liaoning Province, P.R.C.
E-mail: 2387628344@qq.com

**Zhuoyu YAN,** postgraduater student
Shenyang Agricultural University,
No. 120 Dongling Road, Shenhe District, Shenyang, Liaoning Province, P.R.C.

**Mingze XU,** postgraduater student
Shenyang Agricultural University,
No.120 Dongling Road, Shenhe District, Shenyang, Liaoning Province, P.R.C.
E-mail: 812503456@qq.com

**Zhixu WANG,** postgraduater student
Shenyang Agricultural University,
No.120 Dongling Road, Shenhe District, Shenyang, Liaoning Province, P.R.C.
E-mail: 1060641289@qq.com

**Dezhi REN,** Assitant professor, PhD
Shenyang Agricultural University,
No. 120 Dongling Road, Shenhe District, Shenyang, Liaoning Province, P.R.C.
E-mail: rdzi@syau.edu.cn

**Xuewei BAI,** Assciate professor, PhD
(Corresponding author)
Shenyang Agricultural University,
No. 120 Dongling Road, Shenhe District, Shenyang, Liaoning Province, P.R.C.
E-mail: bai-xuewei@syau.edu.cn

**Dejun LIU,** Professor, PhD
Shenyang Agricultural University,
No. 120 Dongling Road, Shenhe District, Shenyang, Liaoning Province, P.R.C.
E-mail: ldjldj@126.com