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Linear compression behaviour of oil palm empty fruit bunches

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Abstract. The study describes the mechanical behaviour of oil palm empty fruit bunches (EFB) as a promising product for pyrolysis production. The EFB samples mixture of moisture content 6.3 ± 0.3 (% d.b.) were grouped into different fraction sizes of 10, 20, 40 and 100 mm. The initial pressing height of each fraction size was measured at 60 mm and compressed at a maximum force of 4,500 N and speed of 10 mm min^{-1} to obtain the force-deformation dependencies using the universal compression machine and pressing vessel of diameter 60 mm with a plunger. Deformation, deformation energy, volume energy and strain were calculated. While deformation decreased with fraction sizes, deformation energy increased. The deformation energies at fraction sizes from 10 mm to 100 mm indicated energy savings of approximately 23%. The optimal fraction size in relation to energy efficiency was observed at 10 mm. The tangent model accurately described the mechanical behaviour of the EFB samples mixture. The results provide useful information for the design of optimal technology for processing EFB for energy purposes.

Key words: mechanical behaviour, mathematical model, energy requirement, biomass material, pyrolysis production.

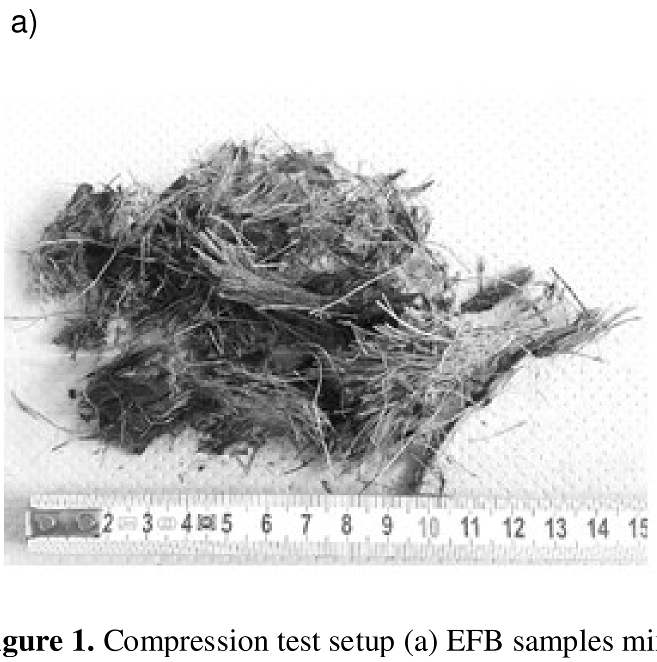
INTRODUCTION

Empty fruit bunches (EFB) of oil palm (*Elaeis guineensis*) are essentially the waste resulting from the processing of palm oil fruits (Verner et al., 2012; Kabutey et al., 2013; Chang, 2014). Nowadays, the global harvested area of oil palm is approximately 20 million hectares (Svatonová et al., 2015; Sembiring, 2019) from which it is clear that the treatment of waste in the production of palm oil plays a key role in eliminating the negative impact on the environment (Basiron & Simeh, 2005; Choong & McKay, 2014). Currently, oil palm empty fruit bunches are processed in several ways including energy generation (Sumathi et al., 2008; Hambali & Rivai, 2017). One of the very common treatments used to process EFB is the thermochemical conversion such as pyrolysis (Chang, 2014; Claoston et al., 2014; Shariff et al., 2014; Awalludin et al., 2015; Setiadi & Hasanudin, 2016). In pyrolysis production relating to high efficiency, it is important to consider pre-treatment of the biomass product, optimal moisture and appropriate porosity and fraction size of the material (Jahirul et al., 2012; Abnisa & Wan Daud, 2014; Malatak et al., 2015). However, the biomass pre-treatment of a particular porosity and fraction size consumes energy, which of course affects the efficiency of the overall processing.

Deformation characteristics of EFB fibres as a part of the composites have already been published in several scientific literatures (Rozman et al., 2004; Karina et al., 2008; Jawaid et al., 2012; Ragunathan et al., 2018). However, information about the behaviour of EFB mixtures under compression loading has not been studied considerably. For this reason, it is vital to understand the mechanical behaviour of EFB under compression loading. Therefore, this study aims to describe the deformation characteristics of EFB mixtures of different fraction sizes, to determine the energy requirement and to describe mathematically the compression process of the EFB mixtures.

MATERIALS AND METHODS

Oil palm empty fruit bunches (EFB) were obtained from North Sumatera, Indonesia. The samples mixture (Fig. 1) were cleaned and manually cut into lengths of approximately 10 mm, 20 mm, 40 mm, 100 mm with 1 mm accuracy using a scissors. The samples were grouped into different fraction sizes: 10, 20, 40 and 100 mm respectively. Each sample group weighed 60 grams. The physical properties of the samples are presented in Table 1. The moisture content of the mixtures was determined using the standard procedure (Farm Pro, model G, Czech Republic). The mass of the sample was determined using an electronic balance (Kern 440–35, Kern & Sohn GmbH, Balingen, Germany). The porosity was calculated from the relationship between the bulk and true densities (Blahovec, 2008). The bulk density was determined from the mass of the sample divided by initial pressing volume $V = 169{,}560$ mm^3 and the true density was determined gravimetrically (Blahovec, 2008).



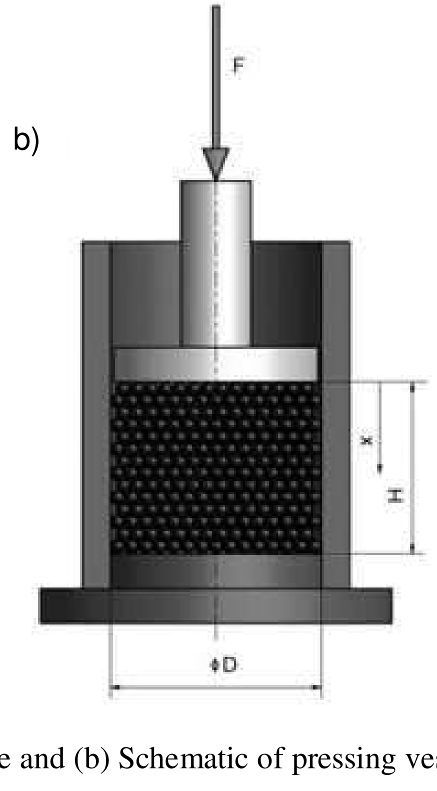


Figure 1. Compression test setup (a) EFB samples mixture and (b) Schematic of pressing vessel with a plunger (Herak et al., 2013).

The pressing vessel of diameter, D of 60 mm with a plunger was used to measure the initial samples pressing height, H of 60 mm was used (Fig. 1). The samples were compressed at a maximum force of 4500 N and speed of 10 mm min^{-1} using the universal compression device (Labortech, model 50, Czech Republic).

Table 1. Physical properties of EFB samples mixture (data are means ± standard deviation)

Moisture content (% d.b.)	Mass (g)	Bulk density (kg m^{-3})	True density (kg m^{-3})	Porosity (%)
6.3 ± 0.3	20.0 ± 0.1	118.0 ± 0.6	612 ± 25	80 ± 3

The deformation energy is characterized by the area under the force-deformation curve which was calculated based on the relation given by Sigalingging et al., 2015. The volume energy was calculated as the ratio of deformation energy to the volume of the pressing vessel (Herak et al., 2013). The strain was determined as the ratio of deformation and the initial height of the sample (Herak et al., 2013). The data were expressed as means of three replicates.

The theoretical description of the force-deformation behaviour of the EPB samples mixture was described based on the tangent curve mathematical model, Eq. (1) (Herák et al., 2013; Sigalingging et al., 2015) as follows:

$$F(x) = A \cdot [\tan(B \cdot x)]^n \qquad (1)$$

where F – compressive force (N); x – deformation of pressed mixture; A – force coefficient of mechanical behaviour (N); B – deformation coefficient of mechanical behaviour (mm^{-1}); n – fitting curve exponent (-). The model fitting was done using the MathCAD 14 software, which uses the Levenberg-Marquardt algorithm (Pritchard 1998) for data fitting.

RESULTS AND DISCUSSION

Determined dependencies between compressive force and deformation are presented in Fig. 3.

The mechanical properties namely deformation energy, volume energy, deformation and strain of EFB samples mixture of different fraction sizes are presented in Table 2.

Table 2. Calculated mechanical properties of EFB samples mixture of different fraction sizes (data are means ± standard deviation)

Fraction Size (mm)	10	20	40	100
Deformation energy (J)	27.7 ± 1.6	31.2 ± 1.7	34.3 ± 1.9	36.0 ± 1.9
Volume energy (J×mm^{-3}× 10^{-4})	1.63 ± 0.23	1.84 ± 0.24	2.02 ± 0.27	2.17 ± 0.27
Deformation (mm)	42.46 ± 2.03	41.28 ± 1.86	39.79 ± 2.05	39.13 ± 1.95
Strain (mm)	0.71 ± 0.03	0.69 ± 0.03	0.66 ± 0.03	0.65 ± 0.03

The results show that the size of the fraction influences the deformation energy and deformation of the mixture. Implying that the bigger the fraction size, the greater the amount of deformation energy required for the deformation of the samples mixture, which also decreases with fraction sizes.

Again, at fraction size of 100 mm, deformation energy and deformation reached limit values, which is assumed constant. This observation is in agreement with several published studies related to the influence of the fraction sizes on the mechanical behaviour of different natural products (Minh & Cheng, 2013; De Bono & McDowell, 2014; Petrů et al., 2014; Mizera et al., 2016; Chaloupková et al., 2018; Sigalingging et al., 2019).

Characteristics with a similar course of deformation energy versus fraction size have been published by several authors (Kashaninejad et al., 2014; Cabiscol et al., 2020; Steffens & Wagner, 2020; Kalman & Portnikov, 2021a, 2021b; Wunsch et al., 2021). The similarity was found in the shape of the curves and in a limit value in which the deformation energy is approaching a constant. Most of the studies focused on the cereal grasses processing or on the processing of substance mixtures intended for the manufacturing of tablets. The above-mentioned studies confirm the influence of fraction size on the energy consumption. Furthermore, the deformation energies at fraction sizes from 10 mm to 100 mm showed energy savings of approximately 23% as shown in Fig. 2. It thus implies that the fraction size of 10 mm is optimal for pyrolysis production.

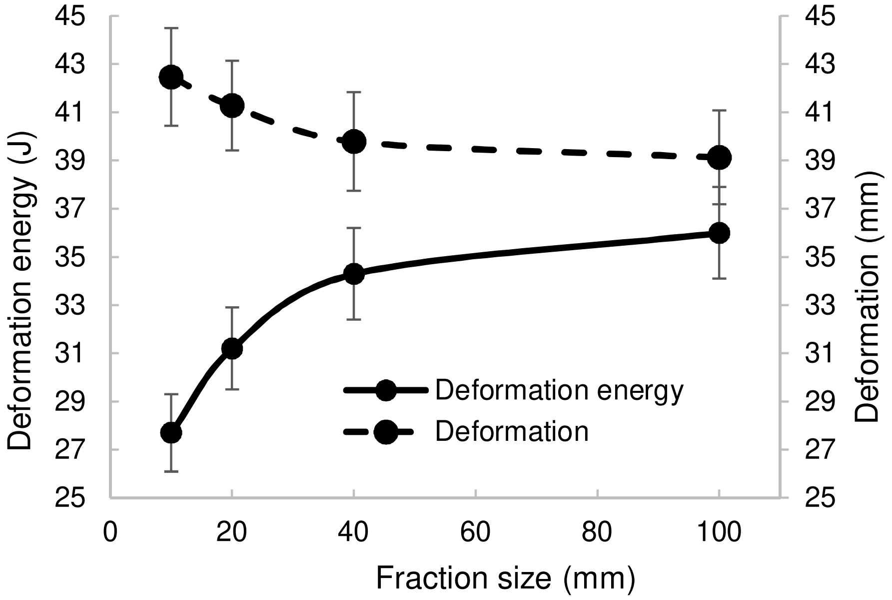


Figure 2. Deformation energy and deformation versus fraction sizes of EFB samples mixture, the error bars are means ± standard deviation.

The determined coefficients of the tangent curve mathematical model and their statistical evaluation are given in Table 3. The tangent model accurately described the mechanical behaviour of the EFB samples mixture (Fig. 3), which confirmed the results of previously published studies focused on the utilization of the tangent curve for various natural materials (Herak et al., 2013; Herák et al., 2014; Sigalingging et al., 2014; Kabutey et al., 2017). The ANOVA statistical analysis showed the significance of the determined coefficients based on the fact that the values of F_{crit} (critical value compares a pair of models) were higher than F_{ratio} values (value of the F-test) and P-value (significance level at which it can be rejected the hypothesis of equality of models) were higher than significance level 0.05. The model's coefficient of determination R^2 for all fraction sizes were between 0.996 and 0.999 indicating its reliability.

Table 3. Determined coefficients of the tangent model and their statistical analysis

Fraction size (mm)	A (N)	B (mm^{-1})	n (-)	F_{ratio} (-)	F_{crit} (-)	R^2 (-)	P-value (-)
10	490	0.029	2	1.79×10^{-3}	4.007	0.966	0.996
20	586	0.030	2	7.75×10^{-4}	4.027	0.978	0.999
40	798	0.029	2	0.015	4.043	0.902	0.998
100	963	0.029	2	0.044	4.043	0.834	0.996

A – Force coefficient of mechanical behaviour, *B* – Deformation coefficient of mechanical behaviour, *n* – Fitting curve exponent, $F_{crit} > F_{ratio}$ or P-value > 0.05 means statistical significance, R^2 is the coefficient of determination

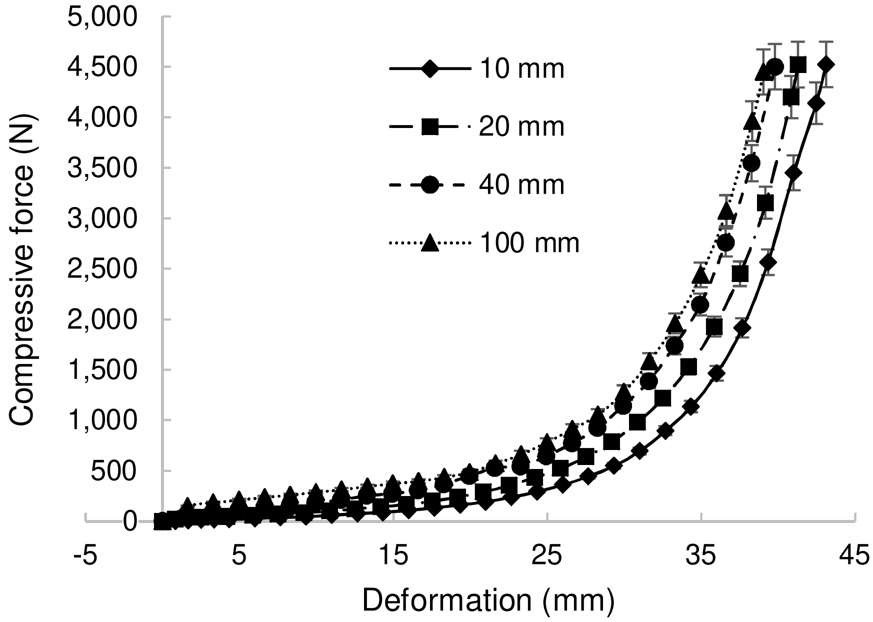


Figure 3. Force-deformation characteristic curves of EFB for different fraction sizes (error bars are means ± standard deviation).

The modern oil palm processing plant produces around 138 tons of EFB per day (Derman et al., 2018; Harahap et al., 2020), which are further pre-treated for various purposes. This pre-treatment corresponds to the energy consumption of 1,380 kWh per day which follows from unit energy consumption of 0.01 kWh per kg of EFB (Jelani et al., 1998; Fiorineschi et al., 2020). Thus, energy saving in terms of fraction optimization could be up to 317 kWh per day in one factory. From already published studies (Svatonová et al., 2015; Sembiring 2019; Setiawan et al., 2020) it follows that the average annual world production of EFB is approximately 300 Mt on which would mean energy savings of approximately 690,000 kWh per year. From this very simple consideration, it is clear how the optimization of fractions could be important in EFB processing.

The results of the study provide the background for the appropriate design of pretreatment technology with optimal energy utilization, and also a tool for creating virtual models based on principles industry 4.0. The derived models can be used for the development of further models which will describe the non-linear mechanical behaviour of EFB.

CONCLUSIONS

The study showed that the fraction size of biomass materials is one of the key factors to consider in pyrolysis process for energy generation. The deformation energies at fraction sizes from 10 mm to 100 mm indicated efficient energy savings of approximately 23%. The amounts of deformation energy and deformation for a fraction size of 100 mm reached the maximum limit of the compression process. The determined coefficients of the tangent model accurately described the mechanical behaviour of the EFB samples mixture. The optimal fraction size about energy efficiency was observed at 10 mm. The results are useful for the design of appropriate technology and the creation of virtual models based on principles of Industry 4.0.

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