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The utilisation of rheological models for describing the mechanical behaviour of oil palm empty fruit bunches under compression loading

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Abstract: This study uses rheological models to describe the mechanical behaviour of oil palm empty fruit bunches (EFB) under compression loading. The oil palm empty fruit bunches were obtained from North Sumatra, Indonesia. The rheological models for different fraction sizes of the mechanical behaviour under compression loading were developed based on a mathematical concept involving spring and dashpot components. The dependencies between fraction size, viscosity, and modulus elasticity were determined and mathematically described for each branch of the rheological model. The general rheological model was developed based on the defined dependencies, considering the deformation and fraction sizes. The determined rheological models and their components could be used as a fundamental building block of digital twins of oil palm empty fruit bunches, and they could be used to optimise the compressing technology and increase the efficiency of the entire pressing process.

Keywords: dashpot; deformation; force; fraction; Newton's laws; Hooke's law; spring; viscoelasticity

Empty fruit bunches (EFB) of oil palm (*Elaeis guineensis*) are by-products or rather waste emerging in the whole oil palm processing chain (Abdullah and Sulaiman 2013; Chang 2014). Currently, the worldwide harvested area of oil palm is about 20 million ha, and thus, the proper treatment of palm oil waste plays a crucial role in reducing or eliminating the negative impact on all components of sustainable development (Basiron and Simeh 2005; Choong and McKay 2014; Svatonová et al. 2015; Sembiring 2019). Adequate information on the mechanical behaviour of empty fruit bunches is essential for designing processing technologies and creating virtual models frequently utilised for treating palm oil waste efficiently.

Empty fruit branches of oil palm have been investigated in several studies related to their mechanical behaviour (Karina et al. 2008; Saller et al. 2021), thermomechanical properties (Chang 2014; Shariff et al. 2014) or their utilisation as a feedstock for bioethanol production (Jahirul et al. 2012; Harahap et al. 2020). However, the scientific literature has published only one suitable model of the mechanical behaviour of empty fruit bunches of oil pam under compression loading (Seller et al. 2021). The published model was based on the tangent curve utilisation of the fraction sizes.

Several mathematical theories of the mechanical behaviour of agricultural materials have already

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been published, namely the tangent curve (Herák et al. 2013; Sigalingging et al. 2015), reciprocal slope transformation (Błaszak and Sergyeyev 2009; Herák et al. 2014), consolidation (Kumhála and Blahovec 2014; Panelli and Ambrozio Filho 2001) and porosities among others (Lizhang et al. 2013; Zhan et al. 2013; Cevher and Oztekin 2021). There are also well-known theories based on the rheological models often used to describe creep and relaxation behaviours. However, these models have not yet been used to describe the mechanical behaviour of agricultural products such as oil palm empty fruit bunches under compression loading. The advantage of employing rheological models is based on the fact that the models are usually assembled from Hooke's members representing elastic behaviour and Newton's members representing plastic behaviour (Mohsenin 1970; Blahovec 2008). These rheological models can be easily transformed into different virtual environments based on numerical simulation, for example, finite element models or discrete element models (Petrů et al. 2012, 2014; Lizhang et al. 2013; Zhan et al. 2013).

The benefits of these models are their relation to the viscoelastic behaviour of the compressed oil bearings crops; thus, the compression speed, oil points, and other factors influencing the oil extraction process could also be analysed employing these models (Minh and Cheng 2013; Petrů et al. 2014; Demirel et al. 2021; Kabutey et al. 2021). The rheological models are also often used as an integral part of the digital twin's concept, originating from visions of Industry 4.0 or Agriculture 4.0 (Fuller et al. 2020; Pylianidis et al. 2021).

Therefore, the aim of this study is to determine the rheological models of the mechanical behaviour of oil palm empty fruit bunches of different fraction sizes under compression loading.

MATERIALS AND METHODS

Sample. The samples of the oil palm empty fruit bunches, originally from Indonesia, North Sumatera (Figure 1), were divided by the fraction sizes 10, 40, 70, 100 and 130 mm; their physical properties are shown in Table 1.

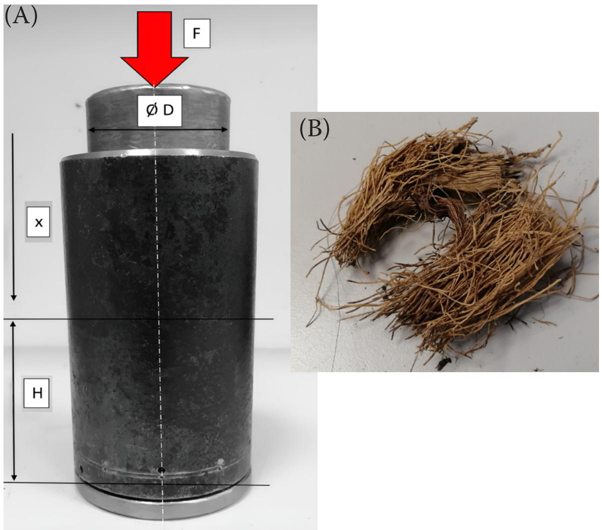

Figure 1. (A) Scheme of the pressing vessel and (B) empty fruit bunches sample
H –initial pressing height; x –deformation; F – compressive force; D –inner diameter

The moisture analyser (model G, Farm Pro, Czech Republic) was used to determine the moisture content of the samples. The mass of the sample was determined using an electronic balance (Kern 440–435, Kern & Sohn GmbH, Germany). The porosity was calculated from the bulk and true densities formula (Blahovec 2008). The bulk density was calculated as the ratio of the sample's mass and initial compressing volume V = 169.560 mm^3, and the true density was gravimetrically identified (Mohsenin 1970; Blahovec 2008).

Compression test. The universal testing device (model 50; Labortech, Czech Republic), with the pressing vessel of an inner diameter of D = 60 mm and an initial pressing height of H = 60 mm, was used (Figure 1) to continuously compress the samples up to a maximum force of 4.500 N with a speed of 10 mm·min^{-1}.

The strain was calculated as the sample deformation divided by the initial pressing height. The acquired results were defined as a mean of five replicates.

Rheological model. The determined force-deformation characteristics were used for the theoretical

Table 1. Physical properties of empty fruit bunches samples

Moisture content (% d.b.)	Mass (g)	Bulk density (kg·m^{-3})	True density (kg·m^{-3})	Porosity (%)
6.8 ± 0.3	21.0 ± 0.2	119.0 ± 0.4	613 ± 26	81 ± 4

data are means ± standard deviation

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description of the EFB samples' mechanical behaviour based on the two branches rheological model (Herák and Sedláček 2017) (Equation 1, Figure 2). The used model consists of two branches assembled from two serial linked components, spring and dashpot. The spring was loaded by compression loading, and the dashpot by tension loading.

$$F(x) = \frac{(S \times \nu)}{H} \times \left[\eta_1 \times \left(e^{\frac{E_1}{\eta_1} \times \frac{x}{\nu}} - 1 \right) + \eta_2 \times \left(e^{\frac{E_2}{\eta_2} \times \frac{x}{\nu}} - 1 \right) \right] \quad (1)$$

where: F – compressive force (N); x – the deformation of the samples (mm); E_{1-2} – moduli of elasticity of the model's branches (MPa); η_{1-2} – coefficients of dynamic viscosity of the model's branches (MPa·s^{-1}); ν – compression speed (s·m^{-1}); H – the initial pressing height (mm); S – the cross-section of the pressing vessel (mm^2).

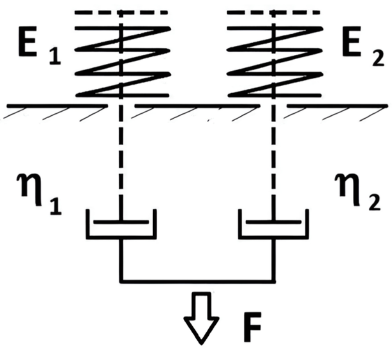

Figure 2. The rheological model with two branches containing two serial linked components, a spring and a dashpot

E_{1-2} – moduli of elasticity ; η_{1-2} – coefficients of dynamic viscosity; F compressive forc

source: (Herák and Sedláček 2017).

The PTC MathCAD Prime software (version 8.0) utilising the Levenberg-Marquardt algorithm was used for the model fitting.

RESULTS AND DISSCUSION

The statistical analysis ANOVA (Table 2) for a given level of significance 0.05 implies that the critical values comparing a pair of models (F_{crit}) were higher than the values of the F-test (F). The significance levels at which the hypothesis of equality of models can be rejected (P_{value}) (Table 2) were higher than the given significance level. This shows that the two-branch model is statistically significant as measured data and models (Figure 3); equation (Equation 1) can be used to fit measured amounts. It is also evident that the curves showed the same shape and trends regarding fraction size as reported in a previously published study on the EFB linear compression process (Saller et al. 2021). This confirms the appropriateness of this model for the description of the mechanical behaviour of oil-bearing crops under compression loading (Sigalingging et al. 2015; Herák and Sedláček 2017; Kabutey et al. 2017; Mizera et al. 2021), considering the size of the fraction (Kashaninejad et al. 2014; Chaloupková et al. 2018; Saller et al. 2021), which follows the results of various published studies (Gharibzahedi et al. 2014; Olayanju et al. 2018). The significant influence of compression speed on the mechanical behaviour of oil-bearing crops, such as the deformation curve, oil points, and deformation energy, has already been proven and published by several studies (Kalman and Portnikov 2021; Wunsch et al. 2021).

Dependencies between fraction size, viscosity and modulus of elasticity for each branch are shown in Figures 4 and 5. It is evident that the mechanical properties of the first branch components are dependent on the fraction size, and the smaller the fraction size, the bigger the viscosity or modulus of elasticity. These dependencies are represented by linear trends given by the equations stated in Figures 4 and 5.

Table 2. Determined values of the general rheological models of empty fruit bunches samples

Fraction size	E_1	η_1	E_2	η_2	F-value	F_{crit}	P-value	R^2
(mm)	(MPa)	(MPa·s^{-1})	(MPa)	(MPa·s^{-1})	–	–	–	–
10	0.159	8.924	0.025	0.961	4.11×10^{-6}	3.960	0.998	0.99
40	0.144	6.793	0.019	0.732	1.12×10^{-5}	3.954	0.997	0.99
70	0.153	7.407	0.023	0.828	8.03×10^{-5}	3.922	0.992	0.99
100	0.140	6.032	0.019	0.686	3.06×10^{-4}	3.932	0.986	0.99
130	0.129	4.628	0.023	0.850	3.10×10^{-5}	3.957	0.995	0.99

E_{1-2} – moduli of elasticity of bunches 1 and 2 ; η_{1-2} – coefficients of dynamic viscosity of bunches 1 and 2; R^2 – coeficient of determination; data were calculated with the coefficient of variation CV = 15 %

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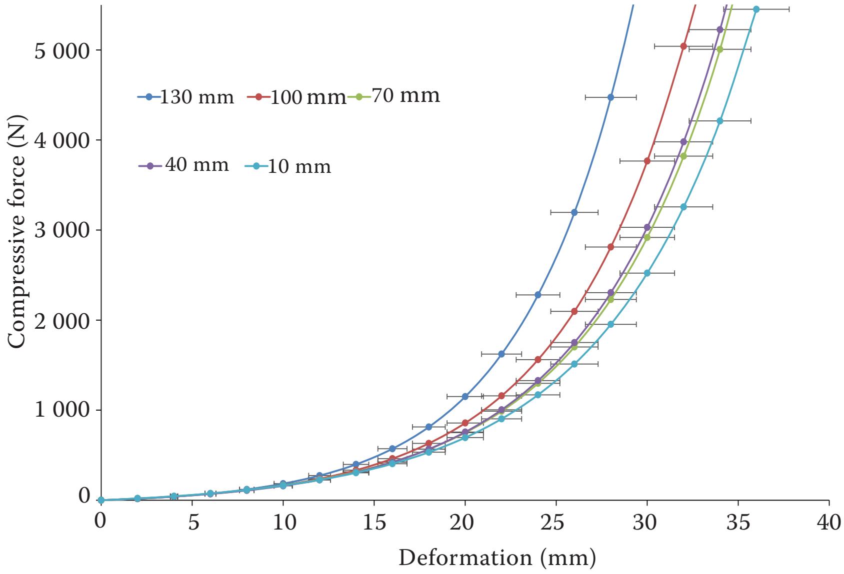

Figure 3. Relationship between compressive force and deformation of empty fruit bunches samples for different fraction sizes

the horizontal error bars present the coefficient of variation 10%

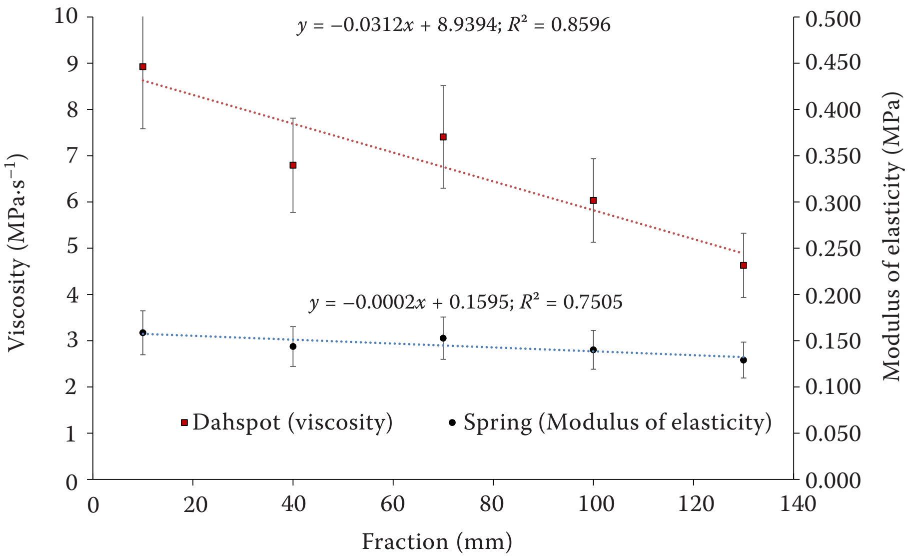

Figure 4. Relationship between viscosity, modulus of elasticity and fraction size of empty fruit bunches samples for the first branch of the rheological model (E_1, η_1)

the horizontal error bars present the coefficient of variation 15%

The mechanical properties of the elements of the second branch are not affected by fraction size, and they can be expressed as a mean of the determined amounts. This study also implies that the equations shown in Figure 4 and Figure 5 present the relationship between viscosity, modulus of elasticity, and fraction size for the first branch of the rheological model and the constant amounts of viscosity and modulus of elasticity for the second branch of the rheological model could be used as an input for the general rheological model given by Equation (1) which express significant amounts concerning the measured data. The advantage of this model is that it considers not only the EFB deformation but also the size of the fraction.

The appropriateness of these claims is confirmed by the ANOVA analysis provided in Table 3, calculated for a given significance level of 0.05. It is evident (Table 3) that the values of F_{crit} were higher than the values of F, and amounts of P_{value} were higher than the given significance.

Table 3. ANOVA results of the fraction sizes of empty fruit bunches samples

FS (mm)	F-value (–)	P_{value} (–)	F_{crit} (–)	R^2 (–)
10	0.003	0.957	4.113	0.921
40	0.015	0.904	4.113	0.935
70	0.094	0.760	4.113	0.956
100	0.048	0.827	4.149	0.934
130	0.002	0.964	4.171	0.923

FS – fraction size; R^2 – coeficient of determination

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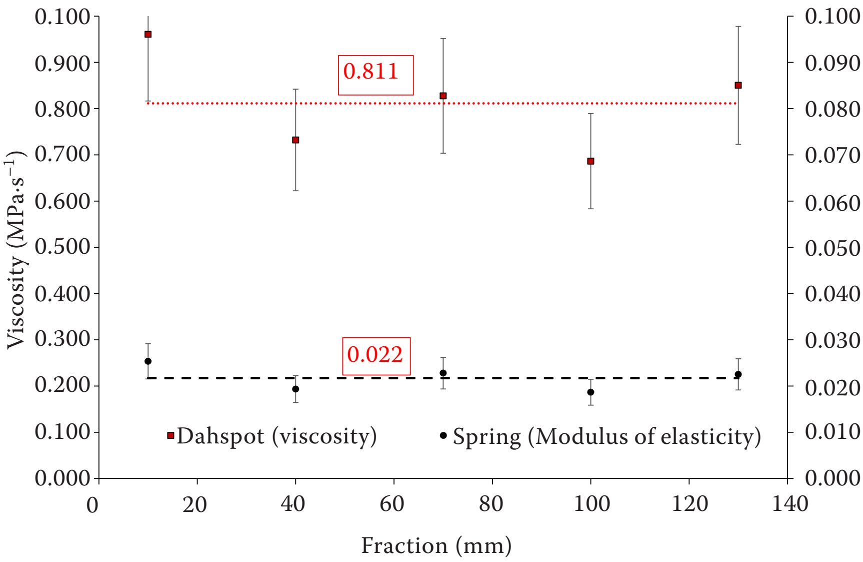

Figure 5. Relationship between viscosity, modulus of elasticity and fraction size of empty fruit bunches samples for the second branch of the rheological model (E_2, η_2)

the horizontal error bars present the coefficient of variation 15%.

It is also evident from the course of Equation (1) that the first branch of the rheological model represented by the higher values of modulus of elasticity E_1 and viscosity η_1 (Table 2) very strongly influence the mechanical behaviour of EFB along the entire length of the deformation curve while the second branch significantly affects only the second half of its deformation curve. Therefore, it can be assumed that the first branch, E_1, η_1, represents the mechanical behaviour of the solid parts of EFB and the second branch, E_2, η_2, represents the mechanical behaviour of the liquid parts. A similar statement can also be found in several publications focused on the rheological behaviour of agricultural products (Aregawi et al. 2013; Suzuki and Hagura 2018; Mizera et al. 2021).

In this study, the determined rheological models, especially their components representing Newton's and Hooke's mechanical behaviour, could be used as a fundamental building block of virtual models of digital twins frequently used nowadays, which are the pillars of Industry 4.0 as well as Agriculture 4.0. From the above, the studies of mechanical and rheological behaviours can be fully understood by applying the emerging digital twin approach. The high level of digitalisation and the use of modern sensors and computer power are tools for introducing technologies in agricultural production, for which the term Agriculture 4.0 concept is often used today.

CONCLUSION

Dependencies between compressive force and deformation of oil palm empty fruit bunches for different fraction sizes were determined.

The rheological models of the mechanical behaviour of oil palm empty fruit bunches under compression loading were developed based on the model with two branches containing spring and dashpot elements for different fraction sizes.

The dependencies between fraction size, viscosity, and modulus of elasticity were determined and mathematically described for each branch of the rheological model. The general rheological model considering the deformation and the fraction size was developed based on these dependencies.

The determined rheological models and their components representing Newton's and Hooke's mechanical behaviour could be a fundamental building block for creating digital twins for oil palm empty fruit bunches.

The characteristics of mechanical behaviour resulting from the determined rheological model could be used to optimise the compression technology and increase the efficiency of the entire pressing process.

For more widespread utilisation of this model, subsequent research should focus, in particular, on the influence of EFB moisture content, the effect of the loading force over time, and, last but not least, the EFB pretreatments.

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