

Evaluation of the possibility of using the Drucker-Prager-Cap model in simulations of the densification process of shredded natural materials

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Abstract. The article presents the preliminary results of numerical simulations of the densification process of shredded waste wood. The purpose of the simulation was to evaluate the possibility of using the Drucker-Prager-Cap model in the field of modeling plastic deformation of shredded biomaterials. The experimental studies allowed the verification of numerical simulations. In the research, the stamp-cylinder assembly of a special construction was used, adapted for assembly on a strength machine. The tests carried out are to constitute guidelines for the construction of machinery and devices for compacting biomass.

Keywords: biomass, natural polymers, sawdust, compaction, Drucker-Prager-Cap model, numerical simulation

1 Introduction

In present times, there is an emphasis on facilitating energy generation from renewable sources. The energy generated in this manner is considered green with low environmental impact. The sources of renewable energy are: the Sun (solar panels, photovoltaic batteries), wind (wind generators), water (hydroelectric generators), earth (geothermal energy sources) and biomass. The term biomass refers to all kinds of natural (organic) materials, which can be processed to generate energy. This includes both organic waste materials from agricultural production (including animal and plant waste), forestry and related branches of industry, including fishing and aquaculture, but also biogases and biodegradable industrial and communal waste fractions such as sawdust and all types of energy crops [1].

In practice, the majority of the biomass is processed before it can be utilized. This process usually entails compaction to form pellet or briquette [2-8]. It calls for utilizing briquetting machines with sufficient efficiency [9, 10]. The possibility to design such a machine depends to a significant degree on the understanding of the compaction process of broken down organic materials which allows to model and analyze it.

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Reviewers: *Grzegorz Domek, Andrzej Kołodziej*

2 Drucker-Prager Cap model

This paper presents an evaluation of the possibility to utilize the ABAQUS software for the purpose of modeling the compaction process of broken down biomaterials. The used software uses several models of plasticity with hardening compaction. These models are: Mohr-Coulomb, Cam-Clay, and Drucker-Prager-Cap. This paper evaluates the utilization of the Drucker-Prager-Cap model.

The Drucker-Prager-Cap model was designed to simulate the behavior of loose soil material such as sand or gravel. However, it is recently being used to model the compaction process of various types of powdered metals or ceramics. It also models compaction processes utilized in the pharmaceutical industry for the production of tablets as well as the compaction processes utilized in the chemical industry [11, 12]. The present work provides an analysis of the feasibility of utilizing the Drucker-Prager-Cap model for the purpose of modeling and simulating the compaction process of broken down wooden waste material such as sawdust.

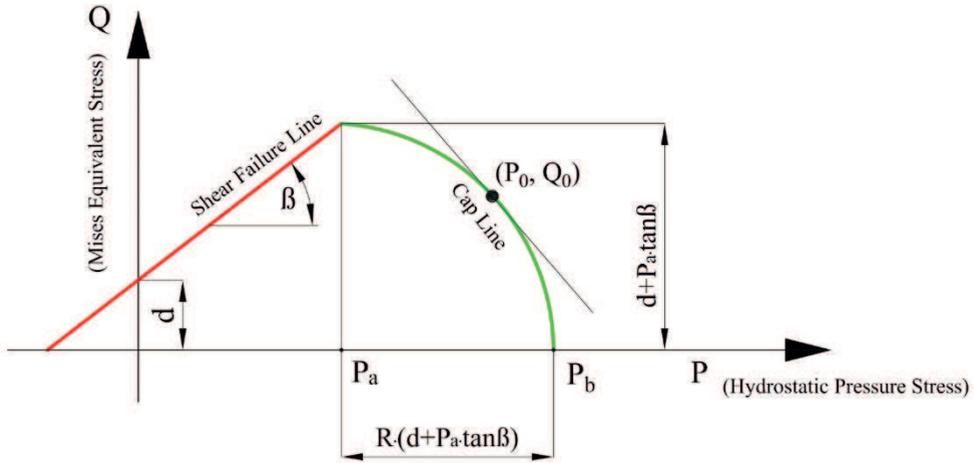


Fig. 1. Modified Drucker-Prager/Cap model: yield surfaces in the $p - q$ plane

The modified Drucker-Prager-Cap model of plasticity simulation implemented in the Abaqus software demonstrates the dependence of the yield point and the pressure exerted on the material. The model itself is established as isotropic and its area of plasticity comprises three segments (Fig. 1). The first one is non-linear and describes the material's shear strength. The second one exhibits non-linear characteristics and represents plastic compaction. The third segment connects the two previous ones. It was introduced in order to maintain an even surface exclusively to facilitate digital implementation [13]. Each area can be described by the following formulae [14]:

$$F_s = q - p \tan \beta - d = 0 \tag{1}$$

$$F_c = \sqrt{(p - P_a)^2 + \left(\frac{Rq}{1 + \alpha - \frac{\alpha}{\cos \beta}} \right)^2} - R(d + P_a \tan \beta) = 0 \tag{2}$$

$$F_t = \sqrt{(p - P_a)^2 + \left(q - \left(1 - \frac{\alpha}{\cos \beta} \right) (d + P_a \tan \beta) \right)^2} - \alpha(d + P_a \tan \beta) = 0 \quad (3)$$

where:

P_a – hardening function depending on the density

R – cap eccentricity

β – the material friction angle

d – cohesion

p – deviatoric stress measure

q – the Mises equivalent stress

α – define a smooth transition surface

The material friction angle may be calculated e.g. from the formula

$$\tan \beta = \frac{3(\sigma_c - d)}{\sigma_c} \quad (4)$$

Whereas R (Cap Eccentricity) can be established with the formula [15]

$$R^2 = (2/3) (P_0 - P_a) / Q_0 \quad (5)$$

whereas P_a (Initial Yield Surface) is derived from the following formula [15]

$$A P_a^2 + B P_a + C = 0 \quad (6)$$

$$A = 2 \tan^2 \beta \quad B = 3Q_0 + 4d \tan \beta \quad C = 2d^2 - 3P_0Q_0 - 2Q_0^2$$

and is finally expressed by the following:

$$P_a = (-B + \Delta_{1/2}) / 2A \quad (7)$$

Whereas P_b (point of intersection of the Cap and the mean stress axis) can be expressed by the following dependence [15]:

$$P_b = P_a + R (P_a \cdot \tan \beta + d) \quad (8)$$

3 Calculation model

The simulation entails representing the compaction process in a cylindrical sleeve with 20 millimeters in diameter. Its digital model is shown on Fig. 2. It consists of a three-part sleeve, a lower, immobile stamp and the upper mobile (compacting) stamp as well as the compacted material. The sleeve is represented as a three-part object. This allowed to record the reaction values in radial direction.

All the sleeve components were modeled as non-deformable by setting the „rigid body” parameter. For the purpose of the analysis, they were assigned the material properties identical to steel. The sawdust was modeled as a deformable solid body with material properties as determined in the experimental examination. In order to determine these parameters, a total of four different types of examination were performed:

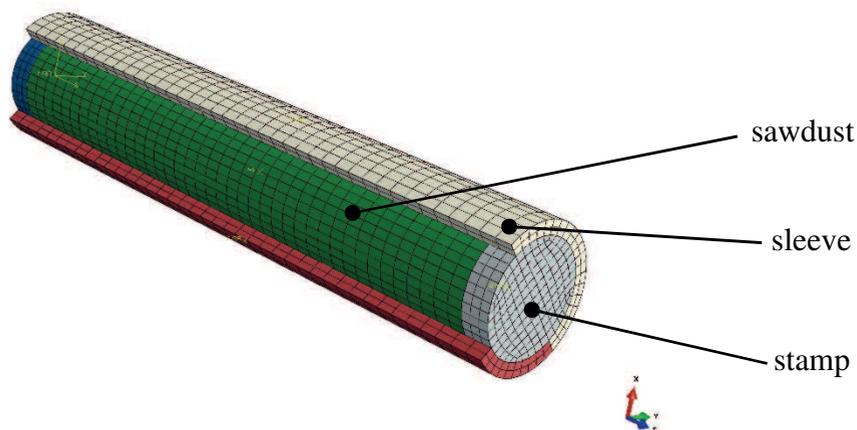


Fig. 2. The simulation model digitalized with a finite element grid

- shearing
- single axis compression
- tri-axial compression
- measuring the friction coefficient

The compaction was carried out for mixed pine and oak sawdust in proportion 1:1. The average humidity was determined to be equal to approx. 10% using a scale-dryer. All material data used in simulation are shown below in Table 1.

Table. 1. Material parameter values used in the simulation for different values of compaction stress

Compaction stress	10 MPa	20 MPa	75 MPa	150 MPa
Material Cohesion	2.3 MPa	8.3 MPa	16.5 MPa	21.9 MPa
Angle of Friction	62.9°	48.8°	57.2°	56.9°
Cap Eccentricity	0.42	0.326	0.24	0.07
Initial Cap Yield Surface Position	0.63	0.63	0.63	0.63
Transition Surface Radius	0	0	0	0
Flow Stress Ratio	1	1	1	1
Mass Density	340 kg/m ³	340 kg/m ³	340 kg/m ³	340 kg/m ³
Young's Modulus	3 GPa	6 GPa	10 GPa	13GPa
Poisson's Ratio	0.18	0.15	0.1	0.05
Friction Coefficient	0.3	0.3	0.3	0.3

The range of movement of the sleeve components and the lower stamp was limited in every direction. The motion of the upper stamp was enabled exclusively along the axis of the stamp, in the direction opposite to axis Z. Between the sawdust material and other items the „General contact” type was assigned. In contact properties, the friction coefficient equal to $\mu = 0.3$ was defined. The research have shown that the average established friction coefficient value is within the range of $\mu = 0.3\div 0.35$. The geometric model was subject to discretized with hex type first order finite elements, with eight nodes and designation C3D8R.

4 Results

As a result of compaction of the broken down material, its density increases. This change is dependent on the displacement of the compacting piston and is not uniform along the entire volume of the sample. The largest degree of compaction is observed near the compacting piston and the sides of the sleeve. It is caused by friction between the sleeve and sawdust. The density of the sample decreases together with the increasing distance from the upper stamp. The difference between the density in the upper part of the sample and the density near the lower stamp is approx. 100 kg/m^3 . The distribution of density at different stages of the compaction is presented at Fig. 3.

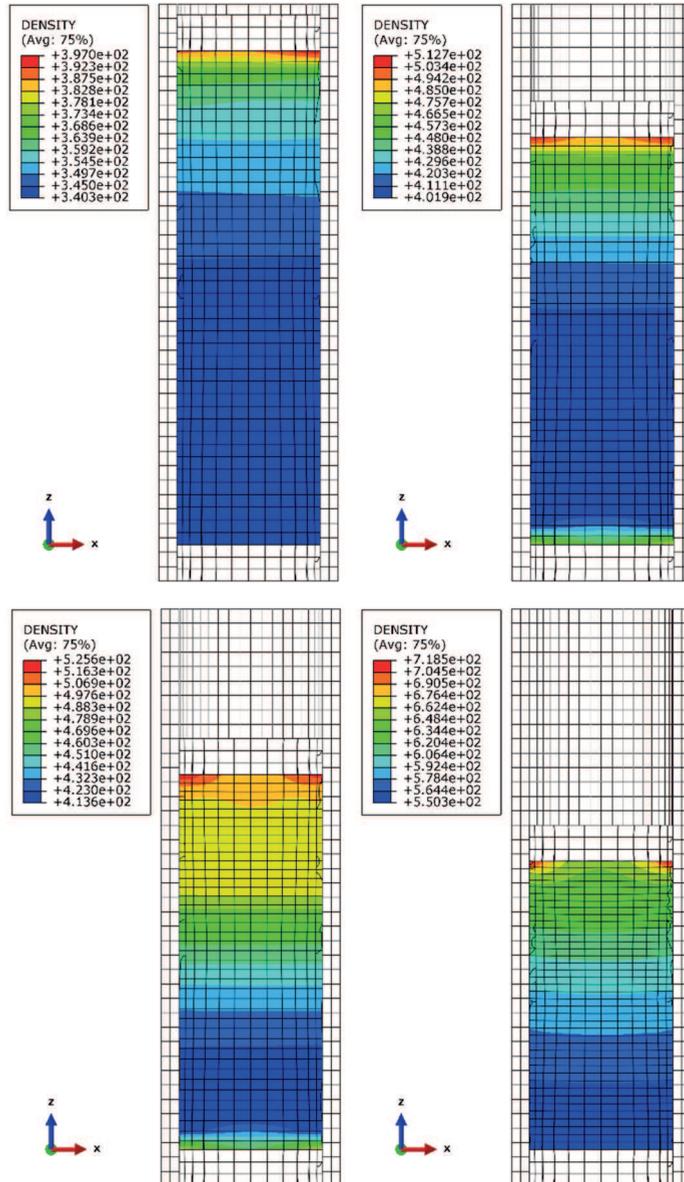


Fig. 3. Results of the simulation of sawdust compaction process for compaction stress 20 MPa – distribution of density in kg/m^3

The results obtained from the simulation were compared to results measured analytically and experimentally. The average density value in the sample after compaction should be equal 600 kg/m^3 . Analyzing the value and distribution of density obtained in the simulation, we ascertain that the obtained values are similar to the actual values obtained experimentally.

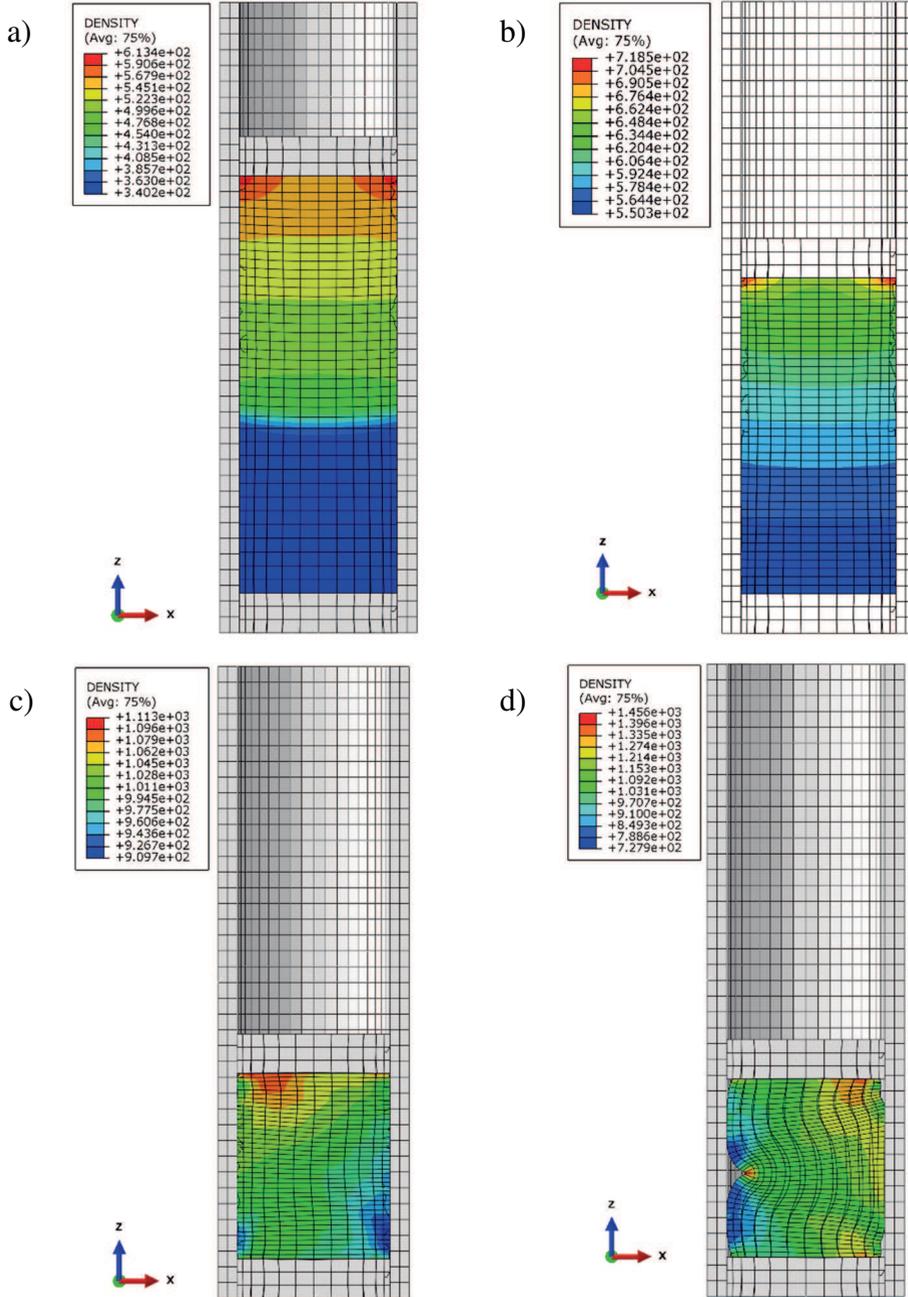


Fig. 4. Results of the simulation of sawdust compaction process for compaction stress: a) 10 MPa, b) 20 MPa, c) 75 MPa, d) 150 MPa (distribution of density in kg/m^3). On c) and d) the modeled material did not behave correctly, because of material parameters which values are constant instead to be defined as a function of density

A similar analysis was carried out for the axial stress values during compaction. The results presented on Fig. 6b indicate that the axial stress near the upper stamp are equal to 20 MPa which corresponds to the force value 6.3 kN at diameter 20 mm. These values correspond to the ones obtained during the experiment (Fig. 5).

The results of numerical simulation for compaction stress 20 MPa are similar with the experiment. Next step, there was checking the numerical model for another values of compaction stress. Results of these simulations were presented on Fig. 4-6. We can notice that values of density and stress are similar with experiment, but distribution of these parameters is not correct for compaction stress 75 MPa and 150 MPa.

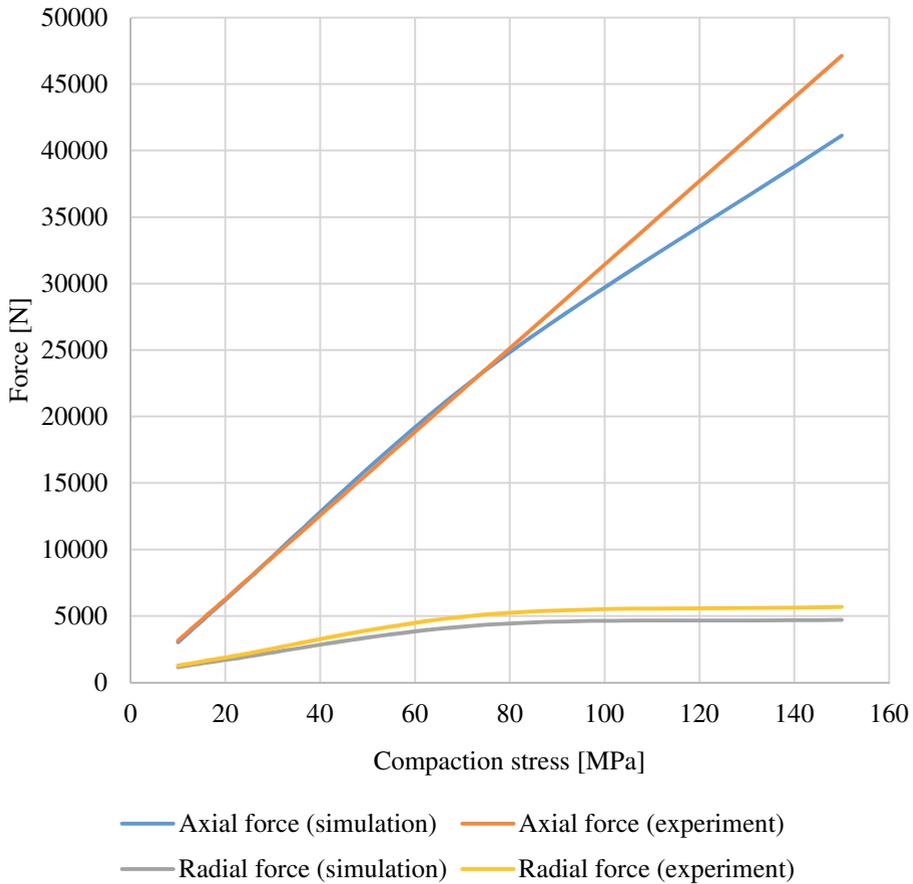


Fig. 5. The characteristic of change of a compaction force as a function of compaction stress – comparison of numerical simulation and experiment

On Fig. 5, there were presented values of axial and radial forces needed to receive appropriate compaction level. These values were calculated during numerical simulation and compared with values exerted during experiments. We can see that all values are similar with one exception for 150 MPa of compaction stress.

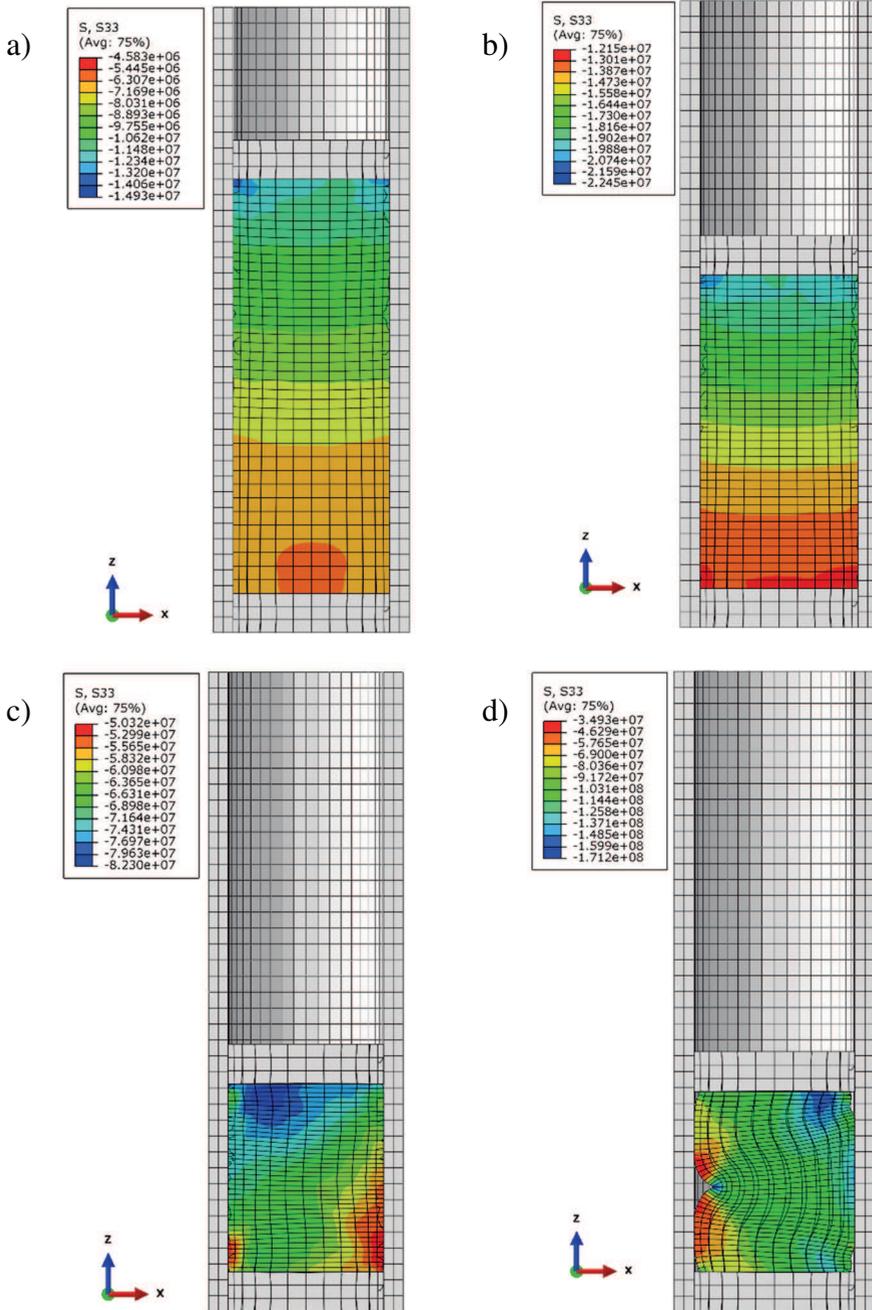


Fig. 6. The distribution of normal stress in the axial direction (direction of compaction) for compaction stress: a) 10 MPa, b) 20 MPa, c) 75 MPa, d) 150 MPa. On c) and d) the modeled material did not behave correctly, because of material parameters which values are constant instead to be defined as a function of density

5 Conclusion

The article presents the results of compaction of broken down waste wooden materials. A numerical model of the compaction process was built employing the values of material parameters obtained in the course of experimental study. The results allow for an assertion that the Drucker-Prager-Cap model can be successfully employed to model the compaction processes of broken down biomaterials.

The numerical analyses were carried out for only few degree of compaction, i.e. for the value of axial stress equal to 10 MPa, 20 MPa, 75 MPa and 150 MPa. Obtaining a greater degree of convergence between the results of simulation and experimental study may prove difficult. It is caused by the fact that the majority of material parameters change together with the degree of compaction. This means that such changes need to be accounted for and all material parameters need to be defined as a function of density.

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