The Cam-Clay model in the application of technological process modeling

M Berdychowski, D Wilczyński, K Talaśka and D Wojtkowiak
Poznań University of Technology, ul. Piotrowo 3, 60-965 Poznań, Poland
E-mail: maciej.berdychowski@put.poznan.pl

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 Cam-Clay model in the field of modeling plastic deformation of shredded biomaterials. The results of simulation was compared with experimental research. The study employed a special stamp-cylinder assembly adapted for mounting on a strength machine. Sawdust was compacted with sufficient force to obtain the desired compressive stress in the sample cross-section. In the experiment, the mixture of oak and pine was used in proportions of 50 % of each material.

1. Introduction
In the contemporary world the demand for energy is immense. Considering that the majority of energy is obtained from the slowly depleting fossil fuels, an increasing number of actions are undertaken to limit energy consumption as well as to increase the share of energy generation from renewable sources. Such energy is considered to be green as its method of generation has a low footprint on the natural environment. Sources of renewable energy include the sun (solar collectors, photovoltaic batteries), wind (wind farms), water (hydroelectric plants), the ground (geothermal energy sources) and biomass. Biomass is understood as all kinds of natural (organic) materials which can be processed into energy. This includes both organic waste from agricultural production (including substances of animal and plant origin), forestry and related branches of industry, including fishing and aquaculture, as well as biogases and biodegradable fractions of industrial and communal waste such as sawdust and all kinds of plants from energy crops [1].
Practically speaking, the majority of the biomass is reprocessed before it can be used. This usually entails its compaction to pellet or briquette form [2–5]. Industrial applications very often utilize compaction. It facilitates transportation and storage, or is simply a stage in the manufacturing process [6–10]. Compaction calls for the use of briquetting machines with sufficient degree of process efficiency [11, 12]. The possibility to design such a machine depends primarily on the degree of knowledge regarding the compaction process of organic material, enabling to model and analyze it.

2. The Cam-Clay model
The present paper demonstrates an evaluation of the feasibility of utilizing the ABAQUS software for the purpose of modeling the compaction process of fragmented materials – waste wood in form of sawdust. The analyzed process is plastic-elastic, therefore material description calls for utilizing one of the plasticity modeling modes available in the software. This paper focuses on evaluating the Cam-Clay model which is used to simulate the behavior of soil materials, mostly deposits similar to clay.
literature provides numerous publications describing the process of compaction of loose materials together with the method to determine material constants necessary to design the model. However, most of these methods are devoted to the compaction of soil or powder materials [13–16].

The clay plasticity model describes the inelastic response of cohesionless soils. This model defines the inelastic behavior of a material by a yield function that depends on the three stress invariants, an associated flow assumption to define the plastic strain rate, and a strain hardening theory that changes the size of the yield surface according to the inelastic volumetric strain [17].

The specific model implemented in Abaqus is an extension of the “modified Cam-Clay” theory. The modified Cam-Clay theory is a classical plasticity model. It uses a strain rate decomposition in which the rate of mechanical deformation is decomposed into an elastic and a plastic part [17].

![Diagram](image)

**Figure 1.** Cam-Clay yield and critical state surfaces in principal stress space [17].

The Cam-Clay model is based on the yield surface:

\[
\frac{1}{\beta^2} \left( \frac{p}{a} - 1 \right)^2 + \left( \frac{t}{Ma} \right)^2 - 1 = 0
\]

where

\[
p = -\frac{1}{3} \text{trace}(\sigma)
\]

is the equivalent pressure stress,

\[
t = \frac{1}{2} q \left[ 1 + \frac{1}{K} - \left( 1 - \frac{1}{K} \right) \left( \frac{r}{q} \right)^3 \right]
\]
is a deviatoric stress measure,

\[ q = \sqrt[3]{\frac{3}{2} (S : S)} \]  

(4)

the Mises equivalent stress,

\[ r = \left( \frac{9}{2} S : S \cdot S \right)^{\frac{1}{3}} \]  

(5)

is the third stress invariant, and \( M \) is a constant that defines the slope of the critical state line, \( a \) is the size of the yield surface, \( S \) is the stress deviator, \( K \) is the ratio of the flow stress in triaxial tension to the flow stress in triaxial compression and determines the shape of the yield surface in the plane of principal deviatoric stresses [17].

3. Model for calculations

The simulation entails representing the compaction process in a cylindrical tube with diameter of 20 mm. The numerical model is provided on figure 2. It includes a three-part sleeve section, lower immobile stamp and upper mobile (compacting) stamp as well as the compacted material. The sleeve is modeled as a three-part component. This allowed to register reaction values in radial dimensions.

| Table 1. Material parameter values employed in the simulation. |
|---------------------------------|-----------------|
| Stress ratio                   | 3               |
| Initial volumetric plastic strain | 0.63            |
| Wet yield surface size         | 1               |
| Flow stress ratio              | 1               |
| Mass density                   | 340 kg m\(^{-3}\) |
| Friction coefficient           | 0.3             |
| Young’s modulus (function of compaction) | 3.3–15.1 GPa |
| Poisson’s ratio (function of compaction) | 0.21–0.055   |

All the sleeve components together with both stamps were modeled as undeformable objects by assigning the property „rigid body”. For the purpose of the analysis, the material characteristics were assigned to these objects. Sawdust was modeled as a deformable solid with material parameter values established in the course of experimentation. In order to determine the values of these parameters, a total of four types of examinations were performed:

- shearing,
- uniaxial compression,
- triaxial compression,
- measuring of friction coefficient.

All the material parameter values are provided in table 1. Because the values of Young’s modulus and Poisson’s ratio vary in the course of the compaction process, a special procedure was called for to account for these changes. Material parameter data were determined for a mix of pine and oak wood at 1:1 weight ratio, with moisture value 10 %.
Figure 2. The simulation model digitalized with a finite element grid.

Freedom of motion was disabled for the sleeve components as well as the lower stamp. The motion of the upper stamp is only enabled along the stamp axis, in direction opposite to the Z axis. Between the sawdust material and the remaining components, the contact type "General contact" was set. For contact characteristics, the defined value of friction coefficient was $\mu = 0.3$. The geometric model was subject to discretization with first order hex type finite elements, eight-node with designation C3D8R.

4. Results
The compaction of the fragmented material causes an increase in its density, the change depends on the displacement value of the compacting die and is not uniform along the volume of the sample. In the axial direction, the density decreases together with the distance from the upper die.

Figure 3. Results of the sawdust compaction simulation – density distribution in kg m$^{-3}$. 
Changes in density in radial directions are even smaller and result from the friction occurring between the compacted material and internal side of the sleeve. The distribution of density changes in the consecutive stages of the compaction process are provided on figure 3.

The results obtained in the simulation were compared to the values established in the course of the experiment. The compared values were both the density of material at the consecutive stages of the compaction process (figure 4), as well as the values of axial and radial force (figure 5) occurring during compaction.

![Figure 4](image)

**Figure 4.** The characteristic of change of a density as a function of compaction stress – comparison of numerical simulation and experiment.

Since the density varies in the axial direction, the comparison of results assumed the density value obtained at the cylinder axis in the direction of three finite elements from the compacting die. The comparison of these values and the values obtained in the course of the experiment indicates a high convergence of the resulting values.

The comparison results for force values is different. Here, we observe a high convergence for radial forces. Whereas for the axial forces, a high degree of convergence is observed for compacting pressure values of 75 MPa. Above this value, the divergence in the force values increase and are equal to approx. 14.9 % for compacting pressure of 150 MPa.
5. Conclusion

The article presents the results of simulated compression process of fragmented wood waste which were compared to the results obtained in the course of experimentation. The aim of the work was to design a numerical model for the discussed process and to verify its correct operation. It was important to determine if the Cam-Clay plasticity model implemented in the Abaqus software is suitable for simulating the compaction process of fragmented biomaterial.

There are several other models implemented in Abaqus for representing material plasticity. Some of them account for the so called material reinforcement as a result of compaction. Therefore, it seems relevant to perform additional simulations utilizing other models and compare the results in order to determine which model offers the closest representation of the discussed process of biomaterial compaction.

An important aspect of the performed simulations is to account for the fact that some material characteristics change together with density. Abaqus software allows to account for this phenomenon by utilizing the so called subroutines. This has a significant influence on obtaining correct results.

6. References

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