Experimental and numerical tests of the compaction process of loose material in the form of sawdust

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Abstract. The paper presents experimental investigations of the compaction process of loose material in the form of sawdust. These were compacted in the sleeve-punch assembly adapted for installation on a strength testing machine. Sawdust was compacted with a force suitable to obtain the desired compressive stress in the sample cross-section. The effect of the composition of the compacted sample was investigated by adding pine sawdust to 50% of the total sample's weight. The experimental compaction process was simulated by building its numerical model using the Drucker-Prager-Cap model. Obtained results of experimental tests carried out on a strength testing machine allowed to establish a numerical model of the sawdust compaction process in the Abaqus program and to assess the possibility of using the Drucker-Prager-Cap model - for numerical simulation of compaction process of loose materials in the form of sawdust.

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

1 Introduction

The technological process of material compaction utilizing the piston technique is commonly employed in, among others, metallurgy, pharmaceutical and automotive industry [1, 2]. Therefore, in order to increase the percentage share of the utilization of biomass in energy generation, it shall be subject to this process in order to improve its physical and chemical properties. The process of compaction utilizing the piston technique for biomass such as straw, sawdust or wood chippings obtained through fragmentation of roadside tree branches using special shredding machines became the subject of interest to numerous researchers [3]. The studies not only focus on examining the process by utilizing testing stations of their respective authors' own design, which allow to identify a number of parameters characteristic for this process, but also attempt, since over a dozen year or so, to model the process numerically or analytically in order to optimize its course and achieve

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Reviewers: *Grzegorz Domek, Andrzej Kołodziej*

the best possible parameters of the end product as well as to reduce energy consumption [4-7]. In order to obtain a product with the required physical and chemical properties, it is necessary to identify the properties of the biomass material in order to select the desirable properties for the compaction process (temperature, compaction force, biomass moisture content, biomass fragmentation and compaction method) [8]. The essential properties of this process have been touched upon by numerous other works, including [9-17].

The biomass in form of broken down wooden material, in particular sawdust, can be utilized in practical form in furniture and construction industries [8]. Examples include the process of rolling in elevated temperature or different techniques of agglomeration utilizing piston or auger mechanisms [14, 15, 17].

The factors influencing the strength and durability of the agglomerate are the type of compacted biomass material (materials), moisture content, size and distribution of particles, process temperature, additives such as binding agent and other substances together with the compaction process parameters (temperature, dimensions of the compacting die, piston head movement speed, etc.) [18, 19]. As mentioned above, the particle size influences the quality of the agglomerate. Therefore, the process of breaking down the biomass and its course is of material importance for the compaction process [20-22].

This study presents the examination of the biomass compaction process in form of mixed pine and oak sawdust. The process was at first numerically simulated using the Drucker-Prager-Cap (DPC) model and afterwards implemented in Abaqus. The experimental study was used for determining the parameters for the numerical model. The laboratory study utilized an agglomeration machine of the author's own design. The construction, methodology and course of the study is further discussed below. The final sections of this paper present example results from the experiment and simulation together with conclusions.

2 The Drucker-Prager-Cap model

The Drucker-Prager-Cap model, further referred to in this study with the abbreviation DPC (Drucker-Prager-Cap), is a model suitable for simulating the behavior of granular soil materials such as sand or gravel [1, 2]. This model is implemented within the Abaqus software, and this paper presents its utilization for numerical simulation of sawdust compaction process. In order for the simulation to be possible, a number of parameters needs to be identified which define the mechanical parameters of the specific material. To this end, one first needs to define the necessary parameters and perform specific experimentations to determine the basis for establishing their values. Fig. 1 presents the Shear Failure Line together with the Cap Line, which are to be determined based on a series of experiments [1, 2].

Fig. 1. Shear Failure Line and Cap Line of Drucker-Prager-Cap model (DPC) [1, 2]

According to Fig. 1, one needs to determine the parameters for calibrating the Drucker-Prager-Cap model, which are defined as follows: d – cohesion coefficient, β – friction angle of DPC model, R – eccentricity parameter of DPC model, P_a – evolution parameter, P_b – this parameter describes the strain hardening of the material during compaction, (P_0, Q_0) is located on the yield surface of the corresponding density [1, 2]. The above parameters can be calculated from the following formulae [1, 2]:

$$d = \sqrt{3} \cdot \tau \quad (1)$$

$$\tan \beta = \frac{3(\sigma_c - d)}{\sigma_c} \quad (2)$$

$$R^2 = \left(\frac{2}{3}\right) \cdot (P_0 - P_a) / Q_0 \quad (3)$$

$$P_a = (-B + \Delta^{\frac{1}{2}}) / 2A \quad (4)$$

$$P_b = P_a + R(P_a \cdot \tan \beta + d) \quad (5)$$

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

$$A = 2 \cdot \tan^2 \beta \quad (7)$$

$$B = 3Q_0 + 4d \cdot \tan \beta \quad (8)$$

$$C = 2d^2 - 3P_0 \cdot Q_0 - 2Q_0^2 \quad (9)$$

$$\Delta = B^2 - 4 \cdot A \cdot C \quad (10)$$

In order to determine the above values to establish the Shear failure line and Cap line (Fig. 1) examination using specialized testing instrumentation was required [1, 2]. To this end, the sawdust material was subject to the following tests: a cycle of compaction and unloading with use of strength testing machine MTS Insight 50 kN, axial compression, tri-axial compression, determination of shear force of sample under specific compression force as well as determining the friction coefficient between the sawdust material compacted with specific force a steel plate. The above experimental tests are characterized in greater detail in the following chapter.

3 Experimental tests

The testing used a 50/50% weigh ratio mix of pine and oak sawdust (Fig. 2). The average humidity was determined to be equal to approx. 10% using a scale-dryer.

Fig. 2. General view of the mixed pine and oak sawdust used in the experimental tests

In the next stage of testing, a strength testing machine MTS Insight 50 kN was employed to subject the prepared sawdust material to a cycle of compression and

unloading. The mix was compacted with a stamp installed in the strength testing machine (Fig. 3) with diameter Ø20 mm, moving within a quill with the same diameter. Inside the quill, the weighted amount of sawdust was placed. Afterwards, the sample was subject to force load F (Fig. 3) with values: 5 kN, 10 kN, 20 kN, 30 kN, 40 kN and 50 kN. After the assumed maximum compacting force (compressive stress) was achieved, the unloading cycle begins. For each pressure value, the examination was repeated three times. This allowed to determine the characteristic (Fig. 3) of force value change during compression and unloading as a function of the testing machine cross-beam displacement.

Fig. 3. The loading-unloading test: a) general view of the stamp-sleeve assembly installed in the strength testing machine, b) example characteristic of the change of force as a function of the displacement of the strength testing machine cross-beam in the 40 kN force load cycle

The examination allowed to determine the change of Young’s modulus as a function of relative density (Fig. 4).

Fig. 4. The characteristic of change of Young’s modulus value as a function of relative density

The compressed cylindrical sample mix of sawdust obtained in the compression and unloading cycle underwent another examination under load in form of axial compression. For every sample compressed with a specific force, the test was repeated three times. Fig 5a presents the compacted cylindrical sample placed on the strength testing machine before compression. Fig. 5b demonstrates an example graph of the change of force during compression of the sample previously compressed under force value 40 kN.

Fig. 5. Compression test: a) view of the cylindrical sample undergoing axial compression at the strength testing machine MTS Insight 50 kN, b) example characteristic of change of value of compression force during axial compression obtained with applied force value 40 kN

This examination allowed to determine the value of internal friction angle (Fig. 11) based on the formula (2).

Fig. 6 presents the view of the sample that was destroyed through action of axial compressing force.

Fig. 6. General view of the destroyed cylindrical sample destroyed through action of axial compressing force

In order to determine the value of Poisson’s ratio ν , a tri-axial compression test was undertaken utilizing a specialized testing station for installation in the strength testing machine (Fig. 7).

Fig. 7. General view of the three-axial sample compression testing station after examination

For the examination, the sawdust was compressed with sufficient axial force to achieve compressive stress at its cross section σ_z equal to, consecutively: 3 MPa, 10 MPa, 20 MPa,

50 MPa, 75 MPa, 100 MPa and 150 MPa. For every stress value, the test was repeated three times. This test allowed to determine the change of Poisson’s ratio as a function of relative density (Fig. 8).

Fig. 8. The characteristic of Poisson’s ratio change as a function of relative density value

In the next step, a specialized testing station was employed to measure the shear force of the compressed sample together with the frictional force of the compacted sample material on the steel plate, which allowed to determine the friction coefficient value μ . As the compacting stamp had a rectangular cross-section with dimensions 20×30 mm, and therefore the dimensions of the sample after compaction were the same, it was necessary to identify the compacting force causing the same value of compressive stress in the rectangular sample caused by the compression with a round stamp with diameter Ø20 mm during the tri-axial compression test. For every stress value, the test was repeated three times. Figs. 9 and 10 present example graph lines obtained from the examination of shear force for the compressed sample and friction force of the sample.

Fig. 9. An example characteristic of shear force as a function of piston displacement

Fig. 10. An example change of friction force as a function of displacement of the piston

The average established friction coefficient value is within the range of $\mu = 0.3\text{-}0.35$. Table 1 presents a breakdown of shear force F_t vales dependent on the compacting stress value σ_z .

Table 1. Breakdown of shear force F_t value for specific values of compacting stress σ_z

σ_z [MPa]	3	10	20	50	75	100	150
F_t [kN]	0.53	0.823	3.99	5.25	5.73	9.64	28.5

The identified shear stress gave grounds to establish the value of cohesion d together with angle of internal friction β .

Figs. 11-14 present the identified base parameters for Drucker-Prager-Cap (DPC) model based on the experiments carried out. The determined characteristics of change of the above mentioned parameters allowed to build a discrete model of the compaction process of the pine and oak sawdust mix.

Fig. 11. The characteristics of change of the coefficient of cohesion d as a function of relative density

Fig. 12. The characteristic of change in radial stress σ_r and compacting stress σ_z as a function of relative density value

Fig. 13. The characteristic of change angle of internal friction value β and parameter R as a function of relative density

Fig. 14. The characteristic of change of parameters P_a and P_b as a function of relative density

The next chapter presents the numerical model of the compaction process of the mixed sawdust material.

4 Numerical tests

The building of the numerical model entailed a representation of the geometry of the sleeve-stamp assembly, taking into account the initial position of the stamp before the compaction during the experimental study together with the displacement traversed by the stamp during sawdust compaction until the set maximum force value is achieved. Fig. 15

presents the numerical model of the sleeve and stamp model intended for simulating the compaction process. The model was constructed utilizing the Abaqus system.

Fig. 15. General view of the numerical piston-based compaction model of sawdust prepared for simulating this process

In order to carry out the numerical simulation, a forced motion equal to $V = 5 \text{ mm/s}$ was assigned to the compacting stamp, which is equal to the displacement velocity of the stamp during the experiment.

As a result of the simulation, a distribution of density of the compacted material was identified, the distribution of normal stress together with the distribution of reaction force value on the compacting stamp. Fig 16a presents the general view of the model after finished simulation of the compaction process presenting the distribution of normal stress in the direction of the axis of compaction (linear motion of the stamp).

Fig. 16. Simulation of the compaction process: a) general view of the discrete compaction model of sawdust after completion of the simulation presenting the distribution of stress (compression) σ_z , b) the characteristic of compression stress σ_z depending on compressing force on the stamp obtained in experimental study

The recorded increase in reaction force at the stamp in the numerical model has achieved a similar value to the compaction force exerted on the stamp by the strength testing machine during experimental study (Fig. 17).

Fig. 17. The increase in compaction force identified during the simulation of the compaction process

It is therefore possible to make a comparison between the normal stress value (compacting σ_z) at the axis of stamp movement obtained from the simulation S_{33} (Fig. 16a) and the experiment (Fig. 16b). According to Fig. 16a, the highest stress value for the compression stress σ_z (marked with blue) is approx. 22.45 MPa, where for the same compaction force exerted on the stamp in experimental data of approx. $F = 6.3$ kN the average stress value was 20.03 MPa (Fig. 16b). The difference between the compression stress σ_z obtained during the experiment and numerical modeling is approx. 12%. Such a result can be considered good.

5 Summary

The paper presents the method of utilization of the Drucker-Prager-Cap model for simulating the compaction process of the mixed sawdust material. To this end, experimental study was carried out to determine a number of parameters as a function of change of density. This allowed to establish the parameters for the DPC model implemented in the Abaqus software.

The functional determination of the above mentioned parameters was possible by numerous experiments that were performed with the necessary number of repetitions. This is proven by the simulation results, in which the values differ in the range of a dozen or so percent in comparison to the results obtained from experiments. For the direction of further study, we anticipate a functional representation of the relations between the values of individual parameters which should serve to reduce the discrepancy between the results obtained from experimental studies and the simulation.

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