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THE INFLUENCE OF SIZE FRACTION ON THE COMPRESSIBILITY OF PINE SAWDUST AND THE EFFECTIVENESS CRITERION FOR DENSIFICATION

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Abstract. Particulate matter from biomass, e.g. wood sawdust, is very diverse. The basic parameter describing the densification process of particulate matter is its compressibility, quantified by the coefficient of compressibility. Knowing this coefficient for a specific material is a basic prerequisite for the application of compressibility equations describing the densification process, and for calculating the workload in the production process of high-grade solid biofuel. This paper deals with a methodology for determining the compressibility factor for sawdust on the basis of experiments to quantify pine sawdust. The experiments were performed in two stages. The first stage was an experimental investigation of the influence of size fraction on the final compressibility of pine sawdust. The results show the behaviour of the pressure load when the parameters of the particulate matter are changed. In the second stage, the experiments are evaluated and optimized to achieve minimum energy input of the process and a maximum degree of densification. The research results will be used to develop new technologies and machinery for biomass densification to achieve a high-grade solid biofuel.

Keywords: biomass, solid biofuel, compressibility, densification of biomass, effectiveness criterion, briquetting.

1. Particulate matter from biomass

For industrial compaction of biomass into the form a fuel, it is necessary to disintegrate the material into a homogeneous, fine fraction. Raw material (dendromass or phytomass) treated in this way has properties similar to those of particulate matter. For research purposes, the raw material will be further considered as referred to here as sawdust.

Particulate matter from biomass consists of solid particles in contact with each other (solid phase), as well as liquid and gaseous phases. The solid phase consists of wooden mass (sawdust), the liquid phase is water, and the gaseous phase is air. The liquid and gaseous phases fill skeletal pores formed by solid particles. The amount of liquid can be very small, and may consist solely of water vapour absorbed on the surface of solid particles. Because the solid particles of biomass are highly porous, surface pores of particles (open) and internal pores (closed) also coexist with these external pores. The surface pores widen the surface of the solid phase, while the internal pores affect some basic physical properties, e.g. density, strength, etc.

The solid particles come into contact with each other. The existence of contacts restricts the freedom of movement of the solid particles, i.e. their motion autonomy, and thus determines the strength and stiffness of the particulate matter. This depends on the number and the strength of the contact bonds which affect the size, shape, roughness and tensile strength of the particle, the character of the interaction between the phases, and the state of the particulate matter. All the factors covered by the structure and its heterogeneity (alternation of films of finer and thicker particles, particles of different composition, different shape and orientation) are referred to as the texture, sometimes called the macrostructure. The most important feature of particulate matter in general is its transformation by the mutual movement of solid particles (intergranular transformation). The degree of motion autonomy of sawdust in the deformation process varies according to the stress. With increasing stress, the degree of physical autonomy decreases, until the stress exceeds the ultimate strength of the solid particles (sawdust) and leads to their disintegration.

Wood sawdust is particulate matter from biomass, and can also be considered as a “consolidated material”. Consolidated materials are solids that are formed by joiningsolid particles into structural elements (by bonding or by consolidating them). For wood sawdust, the consolidation process involves interlacing, compacting and pressing the particles, which are flat. Particulate matter from wood mass suitable for direct compression usually has high porosity and is in the state of loose powder, see Figure 1. The porosity increases in proportion to the grain size and larger fractions. The bulk density of the particulate matter and its pressing is derived from this property of the material.

Figure 1. Particulate matter from wood mass suitable for direct compression.

2. Compressibility of particulate matter from biomass, and a methodology for determining the coefficient of compressibility

The compressibility of particulate matter from biomass is a significant property that occurs during storage, transport, compaction of bulk materials, and a number of other technological operations. When particulate matter is compressed, it densifies. The reduction in the volume of the particulate matter causes a significant increase in the bulk density, and a reduction in porosity. There are two steps in compressing bulk and non-cohesive materials. In the first step, there is a significant change in density as the pores between the particles are filled. Smaller particles fill the spaces between larger particles, and the porosity of the particulate matter is reduced. The size of the pores is approximately equal to the size of the solid particles. The motion autonomy of the particles decreases with reduced porosity until it is completely eliminated. In the second step of compression a further volume change takes place, but is significantly smaller than in the first step. The second change is due to filling of the pore cavities, which are smaller in size than the primary particles. Hard particles therefore become deformed. When the material is exposed to high pressure, the porosity can be reduced to zero. In this case, the system will continuously form solid contacts between particles and particulate matter.

The compressibility of particulate matter is measured by an instrument called an oedometer. A cylindrical sample of particulate matter of height h0 and diameter D_0 is placed in a ring that is loaded by axial compaction force F_Z through the piston (Figure 2). When it is sufficiently rigid, it is assumed that the transverse expansion of the sample is zero, and there is only volumetric reshaping of the particulate matter in the direction of the ring axis. This is uniaxial compression. The oedometer test determines the compressibility curve of particulate matter, which expresses the dependence of compacting force F_Z on the displacement of the oedometer piston h, i.e. the compression of the sample.

The compacting force acting on the piston is created by movement of the crossbeam in the hydraulic press. Compression is carried out at constant speed and displacement. The increase in the force of compaction depending on the movement of the piston is recorded graphically. Data for evaluating particulate compressibility is obtained by the dependence of the compacting force on the displacement of the piston of the oedometer. Values from the compressibility curve for a specific interval of pressure are transformed into the resulting graph as $\log \frac{\sigma}{\sigma_0}$ depending on $\log \frac{\rho}{\rho_0}$, which is approximately linear. The coefficient of compressibility K is determined by the slope of this line.

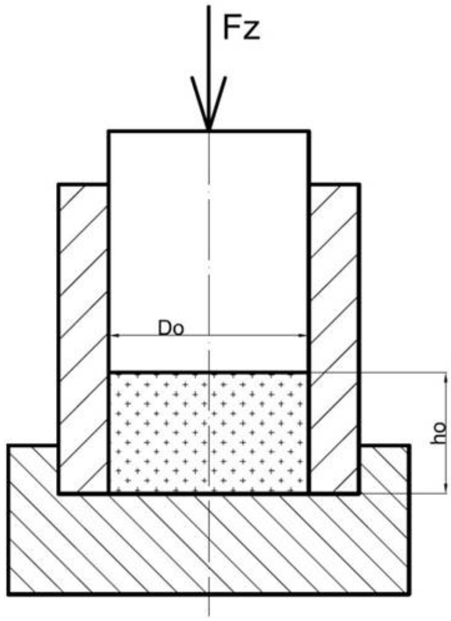

Figure 2. Scheme of the function of an oedometer.

3. Experimental determination of the coefficient of compressibility of sawdust

Experiments were performed to determine the coefficient of compressibility of a material used for producing solid biofuels complying with European standard EN 14961. The material was pine sawdust with various fraction sizes: 0 to 0.5 mm, 0.5 to 1.0 mm, 1.0 to 2.0 mm, 2.0 to 4.0 mm and moisture 15.5 %. For each size fraction, seven densification experiments were carried out at a constant pressing temperature of 20°C. The arithmetic average of the measured values is used in order to obtain the most relevant results. In the experiments, measurements were made of the values of compacting force F_Z and the displacement of the oedometer piston h. The compressibility curve shown in Figure 4 was measured on the basis of the data.

The dimensions of the cylindrical pressing chamber of the oedometer were: diameter $D_0 = 20$ mm, height $h_0 = 229$ mm. Solid biofuels (wood briquettes, wood pellets) made from sawdust are produced under pressure from 90–130 MPa, but at a high temperature. In determining the compressibility of sawdust, the

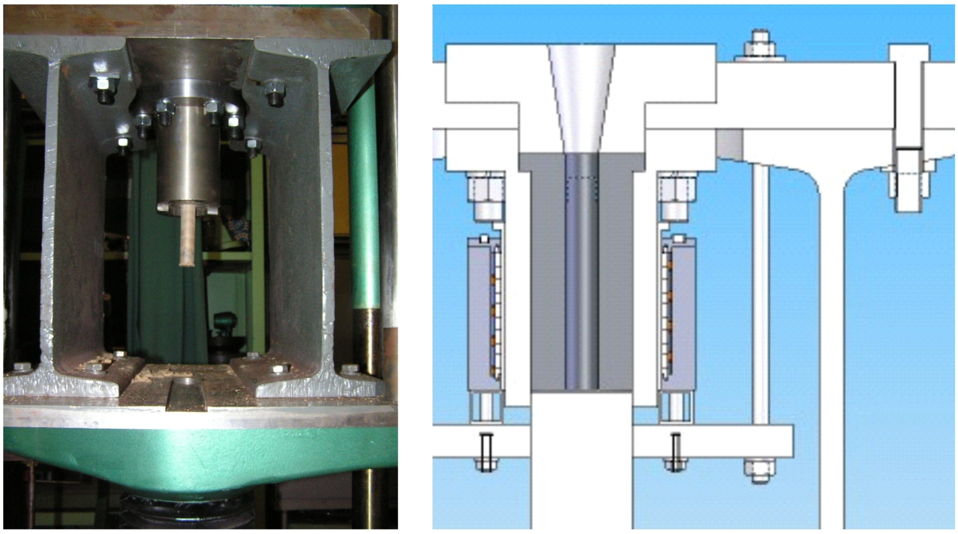

FIGURE 3. The oedometer used in the experiment.

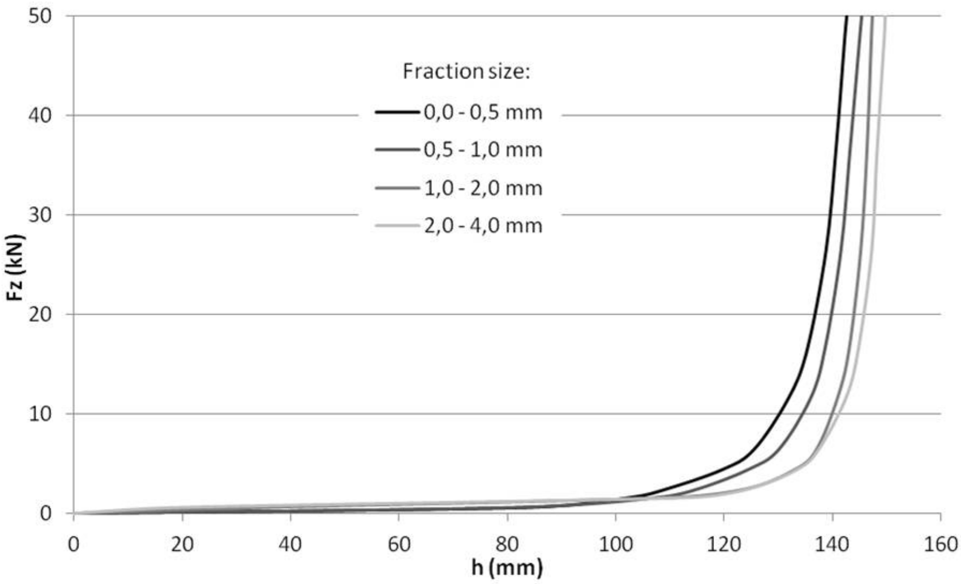

FIGURE 4. Compressibility curve of pine sawdust of various fraction sizes (relative moisture 15,5 %; pressing temperature 20 °C).

interval from 1.9–159 MPa was therefore considered. The lower value of this interval was determined as the lowest pressure at which no measurement errors are caused by the piston entering the pressing chamber.

For a mathematical description of the uniaxial compressibility of sawdust in the oedometer, we used the simplified model of the Balshin formula for compressibility:

$$\frac{\sigma}{\sigma_0} = A\Big(\frac{\rho}{\rho_0}\Big)^K, \tag{1}$$

where σ is the compressive stress at the calculated point, σ_0 is the initial compressive stress (at the starting point of the measurement), ρ is the density of the particulate matter at the calculated point, ρ_0 is the initial density of the particulate matter (at the starting point of the measurement), K is the coefficient of compressibility of particulate matter, and A is a constant regulating the form of a function.

After modification, Equation (1.1) takes the form of a slope equation for a line, where K represents the slope of the line and its value is equal to the tangent of the angle between the line and the positive direction of the x axis. The coefficient of compressibility is simply determined by the slope of this line:

$$\log\frac{\sigma}{\sigma_0} = K\log A + K\log\frac{\rho}{\rho_0}. \tag{2}$$

Calculating the coefficient of compressibility K on the dependence of $\log\frac{\sigma}{\sigma_0}$ to $\log\frac{\rho}{\rho_0}$, it was first necessary to construct a dependence diagram of load σ (pressure) on density ρ. Particular values of load σ at points of the chart were calculated as the ratio of the forces acting at each point and the constant circular surface of the oedometer chamber with diameter $d_o = 20$ mm.

Movement of the oedometer piston h (mm) : **Density** ρ ($\mathrm{kg\,m^{-3}}$)									
Fraction size (mm)		0.0–0.5		0.5–1.0		1.0–2.0		2.0–4.0	
Sample weight m_0 (kg)		0.0128		0.0104		0.0096		0.0066	
Compacting force F_Z (kN)	**Compacting pressure** p (MPa)	h	ρ	h	ρ	h	ρ	h	ρ
0.0	0.0	0.00	178	0.00	145	0.00	134	0.00	92
0.6	1.9	84.00	281	81.67	225	35.00	158	20.00	101
1.6	5.1	102.67	323	107.67	273	110.67	258	113.67	182
2.5	8.0	109.67	341	115.33	291	124.33	292	124.67	201
4.4	14.0	119.67	373	124.33	316	133.00	318	133.33	220
6.4	20.3	125.50	394	130.00	334	137.00	332	137.33	229
11.5	36.6	131.83	419	135.83	355	140.83	347	142.33	242
16.4	52.2	135.33	435	138.50	366	143.00	355	144.67	249
26.4	84.0	138.83	452	141.50	378	145.17	365	147.17	257
36.5	116.0	140.67	461	143.17	386	146.33	370	148.17	260
48.0	152.6	142.33	470	145.00	394	147.17	373	149.50	264
50.0	159.0	142.67	472	145.33	396	147.33	374	149.67	265

Table 1. Measured and calculated values obtained for densification of sawdust.

The loads at particular points of the chart were calculated from the following relationship:

$$\sigma = \frac{F_Z}{S_0}. \tag{3}$$

Similarly, the density of the particulate matter at different points of the chart was calculated from the relationship:

$$\rho = \frac{m_0}{V_0}, \tag{4}$$

where m_0 was the weight of pine sawdust for various fraction sizes in the initial compressed volume $V_0 = 7.18885 \cdot 10^{-5}\,\mathrm{m^3}$. All measured and subsequently calculated values are shown in Table 1. Then the chart showing the dependence of load ratio $\frac{\sigma}{\sigma_0}$ on density ratio $\frac{\rho}{\rho_0}$ was created. In the chart, the values σ_o and ρ_o are initial values, i.e. the lowest load and density value determined by measuring with the oedometer (Figure 5).

Finally, the resulting curve relating $\log\frac{\sigma}{\sigma_0}$ and $\log\frac{\rho}{\rho_0}$ was replaced by a standard linear approximation (Figure 5), the slope of which represents the desired coefficient of compressibility K. It should be mentioned that a linear approximation can be used in cases where the shape of this curve is almost linear. For fraction sizes 0.0–0.5 mm and 0.5–1.0 mm the curve is very similar to a line. The curve of this dependence changes gradually from linear to exponential as the fraction size increases. Since we want to compare values while using the same method, we consider the linear approximation.

Fraction size (mm)	**Coefficient of compressibility** (–)
0.0–0.5	7.97
0.5–1.0	7.09
1.0–2.0	4.07
2.0–4.0	3.60

Table 2. Coefficient of compressibility values. Boundary conditions: particular matter — pine sawdust; Relative moisture — 15.5 %; Pressing temperature — 20 °C; Compacting pressure — 1.9–159.0 MPa.

4. Results

Based on experiments on densification of pine sawdust with a constant relative moisture content of 15.5 %, and a constant temperature of 20 °Cwith a compression pressure range from 1.9 to 159.0 MPa (corresponding to the compression force range from 0.6 to 50.0 kN), it can be concluded that the coefficient of compressibility decreases with increasing fraction size for this type of particulate matter. The resulting compressibility coefficient approximation depends on the mean of the examined fraction size ranges for the boundary conditions shown in Figure 6. A summary of the experimental results is presented in Table 2.

The evaluated experiments also introduce a second output — a comparison of various sawdust fraction sizes and the differences in their density during compression. Figure 7 and Figure 8 show that the difference in density of wood sawdust, at the same

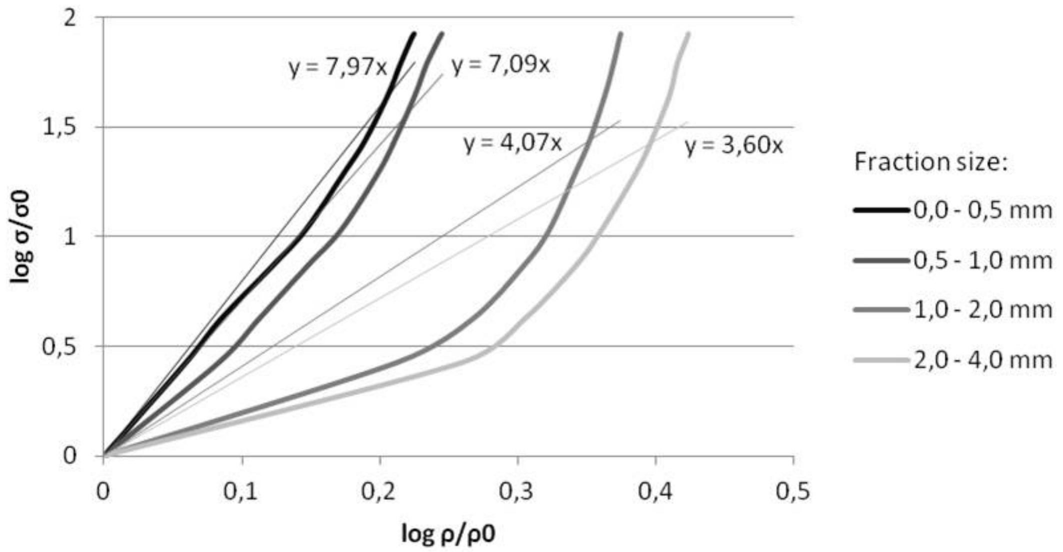

Figure 5. Dependence of log $\frac{\sigma}{\sigma_0}$ on log $\frac{\rho}{\rho_0}$ and linear approximation.

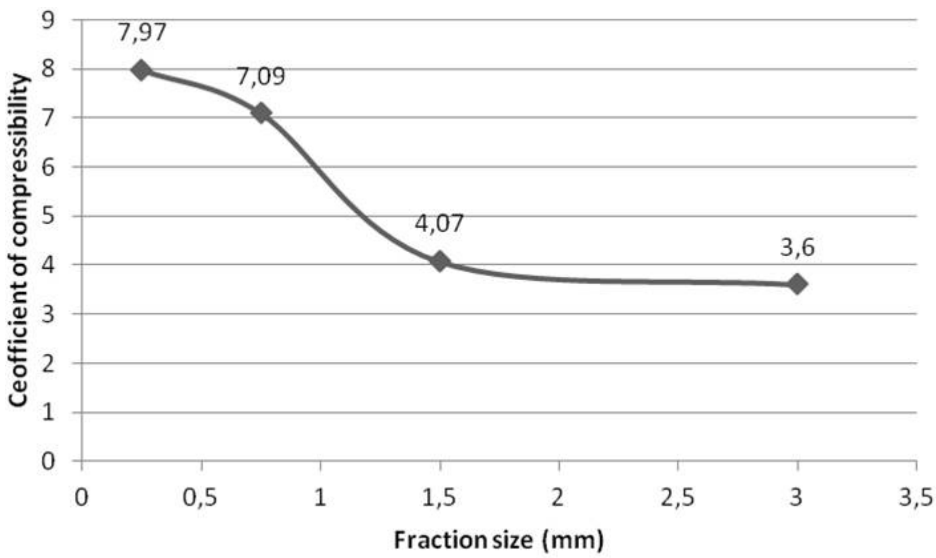

Figure 6. Resulting character of approximated coefficient of compressibility values, depending on the mean of the fraction size ranges.

compacting pressure, increases as the fraction size decreases. This fact has a big impact on the energy efficiency of the whole densification process. The compacting pressure is the input energy required for the densification process. Determining its effect on the density difference is of great benefit for the economy of the densification process, and for the process of solid biofuel production.

In order to compare the minimum energy input for the process and the maximum degree of densification for the four size fractions at a specific pressure value, the Effectiveness Criterion for Densification was created and calculated according to the relationship:

$$\mathrm{ECD}_i = \frac{\rho_i - \rho_{i-1}}{p_i} \quad (\mathrm{kg\,m^3/MPa}). \tag{5}$$

This criterion represents the ratio of the density difference per unit of pressure ($\mathrm{kg\,m^{-3}/MPa}$). A higher value of the criterion for a specific pressure value indicates higher energy efficiency of the densification process. As is shown in Figure 7 and Figure 8, the Effectiveness Criterion for Densification increases as the fraction size of the sawdust decreases, which means higher energy efficiency of densification.

Wood sawdust is a “living” material. Therefore, while it is being pressed, there is a difference in the coefficient of compressibility not only due to the differences in fraction size, but also due to the changes in the pressing temperature and moisture content. It should also be noted that in practical production of solid biofuel by densification of wood sawdust, the raw material is of varying fractional composition, i.e. it does not have a uniform fraction size. The fractional composition of the raw material has a major impact on its compressibility. This will be a topic for future research on biomass compressibility.

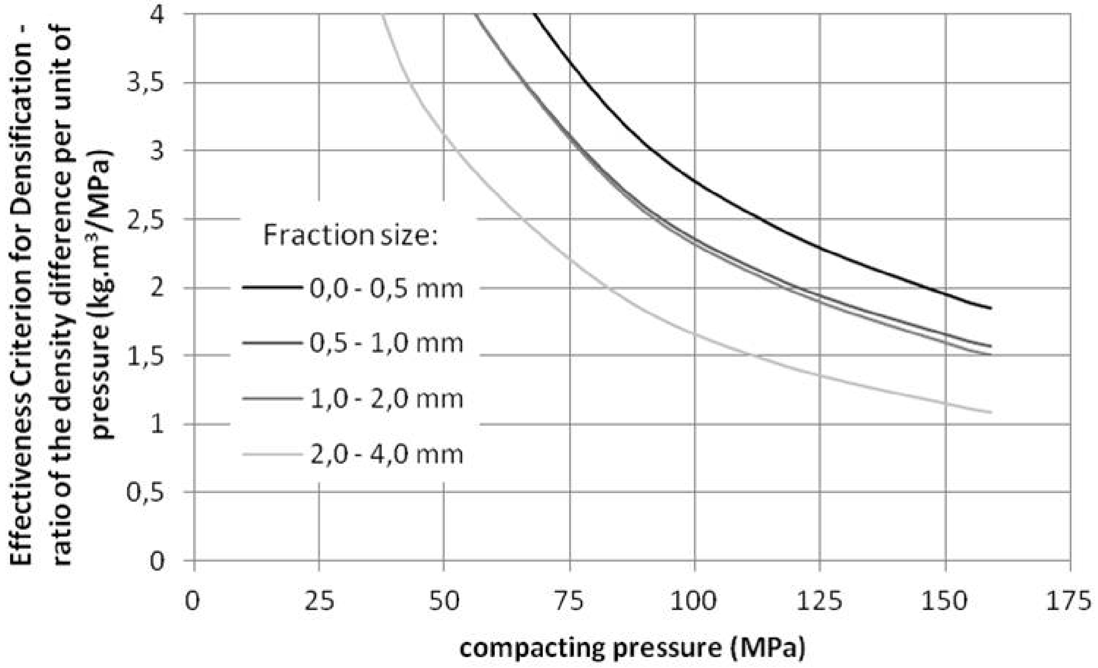

FIGURE 8. Effectiveness Criterion for Densification of sawdust — detail.

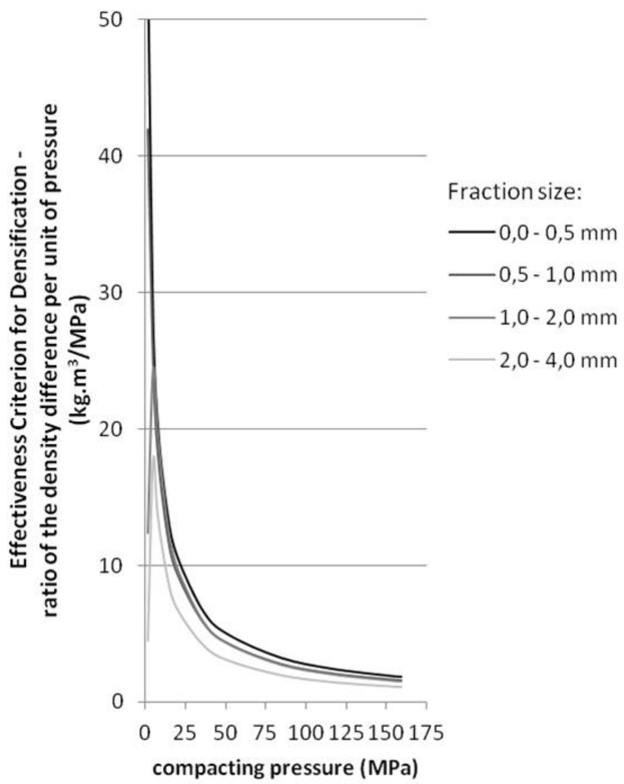

FIGURE 7. Effectiveness Criterion for Densification of sawdust — whole area.

5. Utilizing the coefficient of compressibility for sawdust in practical applications

The coefficient of compressibility for wood sawdust is a very important parameter that describes the behaviour of this particulate matter during the densification process into the form of a high-grade solid biofuel. There are many biomass densification technologies that are used for producing solid biofuels. On the basis of the mathematical model describing these technologies, and on the basis of knowing the coefficient of compressibility for a specific type of biomass, it is possible to calculate the exact pressing forces, the torques and the complex pressure ratios of the densification process. This data is needed for designing and optimizing the structure of compacting machines and their functional components. With this data, it will be possible to optimize machine design in terms of strength, energy and minimizing production costs.

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