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Original Research

The *Andropogon gerardii* Compaction Process in Terms of Ecological Solid Fuel Production

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Abstract

Our paper presents the results of a study that evaluated the effects of moisture content of plant biomass (*Andropogon gerardii*) and average particle size on compaction parameters, susceptibility of raw material to compaction, and quality of the obtained agglomerates in the context of energy use. Moisture content of the material was between 10 and 18%. Compaction of the raw material was carried out using the ZWICK Z020/TN2S strength tester and a closed compression die assembly. It was found that along with the growth of moisture content, the following processes were observed: increase in density of plant biomass in the chamber, decrease in density of the agglomerates (after 48 h storage) and compaction work, and increase in expansion of the agglomerate. The increase in moisture content enhanced susceptibility of the raw material to compaction and caused deterioration of the quality of agglomerates in terms of their strength. With an increase in average particle size, density of the agglomerate decreased, work of compaction increased, and strength of the agglomerate decreased. It was shown that the selection of appropriate parameters of the process promotes energy conservation, which is particularly relevant in terms of the impact of the agglomeration process on the environment.

Keywords: compaction, *Andropogon gerardii*, moisture content, average particle size, ecological solid fuel

Introduction

The recent decision of the European Council to reduce CO_2 emissions by 40% by 2030 should contribute to the further development of the renewable energy sector. Plant biomass has significant energetic potential as a renewable source of environmentally friendly energy [1-3]. Energetic use of the biomass is possible through combustion, gasification, and pyrolysis. The development of this sector will occur mainly based on solid biofuels from plant biomass. Biomass used as an energy carrier includes agricultural wastes (straw, hay) and wood residues, including wastes

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derived from the timber industry (wood particles, shavings, sawdust), with targeted energy crops (e.g., willow, poplar, Jerusalem artichokes, *Miscanthus giganteus*).

Due to the possibility of diseases and pests that can threaten crops, farmers were forced to search for new plant species. *Andropogon gerardii*, an American prairie grass, can be taken as an excellent example of such plants. This plant has good energy features [4-6]. This species is a type C4, like *Spartina*, *Miscanthus*, which generally do not produce seeds. Even occasionally issued, they have a poor lifespan. In climatic conditions of Europe (and especially in Poland) this species does not raise concerns about its uncontrollable spread due to relative late seed ripening, slow seedling establishment, and significance competition from local flora components [7].

These plants, due to their low density (which hampers transport, storage, and dosage to boilers) and low calorific value (in relation to the volume unit), are difficult to distribute in natural form. Energy crops of low density value require a change of their original form into agglomerates, which is obtained by briquetting or pelleting of the loose material [8-11].

These processes require knowledge of pressurized compaction of plant materials. An important factor is to determine the course of compaction and quality of the product. Studies on pressurized compaction of plant materials on a laboratory scale are mainly conducted using devices with operating systems called "cylinder-compacting piston" [12, 13]. They help specify the parameters of the compacting process, including the energy intensity of compaction and susceptibility of the material to compaction. Our studies, along with studies conducted by other authors, have shown that the course of the process and the resulting product of an appropriate mechanical strength depend on physical and chemical properties of the raw material [14-19].

In the process of compaction, the moisture content of the material is of particular importance [20-24]. The obtained parameters of pressurized agglomeration are also dependent upon physical properties, including the average size of the biomass particles [12, 21-23, 25]. This study is a continuation of research that evaluated the impact of process conditions on the course of compaction of plant materials.

The objective of this study is to determine the impact of moisture content and average particle size of *Andropogon gerardii* on compaction parameters and the quality of the resulting agglomerate.

Materials and Methods

Our experiment was conducted using the long-term grass *Andropogon gerardii*. This species is sensitive to weeds, especially in the initial two years of cultivation [5]. Depending on soil fertility, the quantity of crop was between six and 24 tons d.m. per hectare. It may also be useful for the recultivation of industrial areas.

In this study, the raw material was purchased from the Plant Breeding and Acclimatization Institute at the National Research Institute in Radzikow. Studies conducted in this institute showed that the heat of combustion of the raw material was approximately 17.5 MJ/kg d.w., and the ash content was approximately 5%.

For the study of pressurized compaction, ground raw material was used. *Andropogon gerardii* was ground using an H 950 shredder utilizing sieves of three different diameters: 4, 7, and 10 mm. By this method, three samples of the tested material were characterized by different average particle sizes that were obtained.

Average particle size was determined for ground samples of *Andropogon gerardii*. Measurements were made in accordance with PN-EN 15149-2:2011 using a SASKIA Thyr 2 sieve shaker (using a set of sieves with mesh sizes: 0.095, 0.18, 0.315, 0.5, 0.8, 1.0, 1.2, 1.6, 2.0, and 3.2 mm; sample weight of 100 g; and sieving time of 5 min). The average particle size of samples of the investigated material was d_s = 0.85 mm, d_s = 1.34 mm, and d_s = 1.81 mm.

The compaction process was carried out for samples of ground material characterized by moisture content of 10, 12, 14, 16, and 18% (±0.2%). The moisture content was determined by oven-drying method in accordance with PN-EN 14774-1:2010. The given moisture content was obtained by drying or by adding water to the sample material.

Compaction studies were performed according to the procedure presented by Laskowski and Skonecki [26]. Compaction of the raw material was carried out using the ZWICK Z020/TN2S strength tester. Our study also used a closed compression die assembly (Fig. 1). The diameter of the compression chamber was 15 mm, the temperature of the cylinder (compacted material) was 20ºC, and the piston speed was 10 mm per min. Weight of material sample was 2 g. Compaction was carried out for the maximum compaction force F_{max} = 20 kN, for the maximum specific piston pressure on the material equals 113 MPa. Every compaction process was performed in three replications.

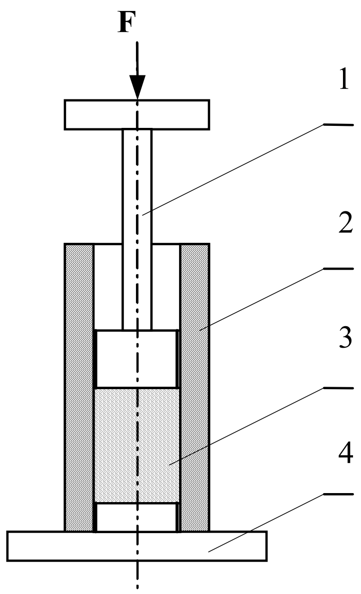

Fig. 1. Scheme of the closed compression die assembly: 1 piston, 2 cylinder, 3 compacted material, 4 base [12].

As a result of the measurement, a compaction curve (correlation between compaction force F and piston speed; a description of the curve can be found in [26]) was obtained, for which the parameters of the process were evaluated. The maximum density of the material in chamber ρ_c and specific compaction work L_c were determined. For the resulting briquette, density of the agglomerate after 48 h of storage ρ_a was determined.

The coefficient of material susceptibility to compaction k_c was calculated:

$$k_c = \frac{L_{c'}}{(\rho_c - \rho_n)} \quad (1)$$

...where:
$L_{c'}$ – specific compaction work [J·g^{-1}],
ρ_n – initial bulk density of raw material [g·cm^{-3}].

The quality of the agglomerate in terms of mechanical strength was determined in a compression test with the use of a ZWICK Z020/TN2S strength tester (piston speed 10 mm·min^{-1}). The agglomerate with a diameter d and length l was compressed along the perpendicular axis until damage (crack), and the maximum braking force F_n was determined. The so-called agglomerate mechanical strength δ_m [MPa] was calculated using the following formula [27]:

$$\delta_m = \frac{2F_n}{\pi\, dl} \quad (2)$$

Correlation analysis between the moisture content of material, its granularity, and compaction parameters of the process was performed using the statistical procedures of STATISTICA program, at a significance level of $\alpha_i = 0.01$. Plots showing these correlations, regression equations, and the values of coefficient of determination R^2 are presented in Figs. 2-6.

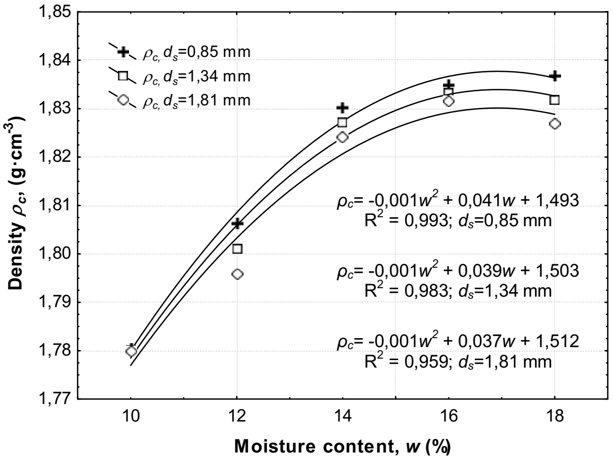

Fig. 2. Correlation between density of the raw material in chamber ρ_c and moisture content w for three average particle sizes of material d_s.

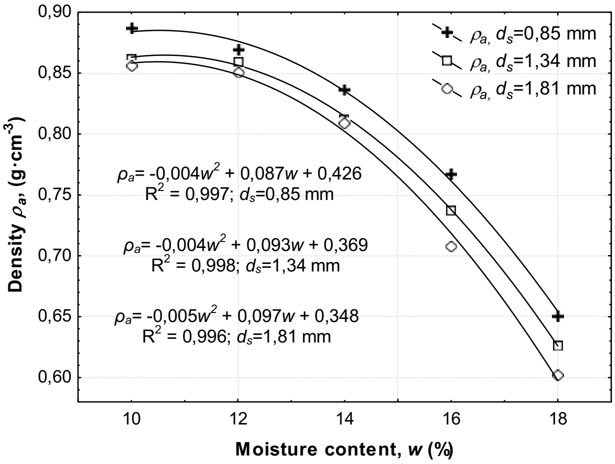

Fig. 3. Correlation between density of agglomerate ρ_a and moisture content for three average particle sizes of material d_s.

Results and Discussion

Changes in the density of raw material in the chamber and agglomerate are illustrated in Figs. 2 and 3. From the resulting data, it can be concluded that with increasing moisture content, the density of the material in chamber ρ_c (only a slight decrease in density in the range of 16-18% of moisture content was observed) increased, and the density of agglomerate ρ_a decreased.

For the tested raw material, the highest values of ρ_c and ρ_a parameters related to the lowest average particle size d_s = 0.85 mm. For this particle size, the range of density variation within the moisture content range of 10-18% ranged from 1.78 g·cm^{-3} to 1.84 g·cm^{-3} for ρ_c, and from 0.89 g·cm^{-3} to 0.65 g·cm^{-3} for ρ_a. By contrast, the lowest values of the density were obtained for raw material compaction with the highest average particle size d_s = 1.81 mm. Densities for this average particle size were: ρ_c from 1.78 g·cm^{-3} to 1.82 g·cm^{-3} and ρ_a from 0.86 g·cm^{-3} to 0.6 g·cm^{-3}. The resulting density of the raw material in the chamber ρ_c for d_s = 0.85 mm was about 2% higher than this density for material compaction of d_s = 1.81 mm.

In contrast, for the agglomerate density ρ_a in terms of compaction of the raw material of d_s = 0.85 mm, density was higher by about 5% in comparison to the density achieved for *Andropogon gerardii* of d_s = 1.81 mm. Similar results were also found in studies conducted by Mani et al. [21]. In this case, the change in the diameter of a mill shredder from 3.2 to 0.8 mm caused – in comparison to most of the tested materials – an increase in the density of obtained agglomerates.

The correlations between specific compaction work $L_{c'}$ and moisture content (w) of the raw material for the three average particle sizes of the raw material are shown in Fig. 4. The work decreased with increasing moisture content of *Andropogon gerardii* for each average particle size d_s. The highest values of this work were obtained in terms of

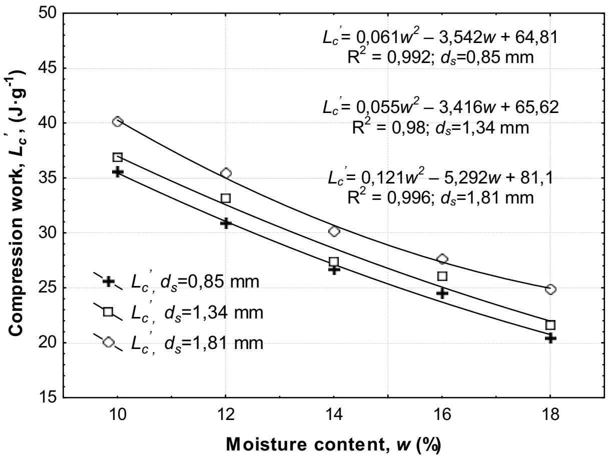

Fig. 4. Correlation between specific compaction work $L_{c'}$ and moisture content for three average particle sizes of material d_s.

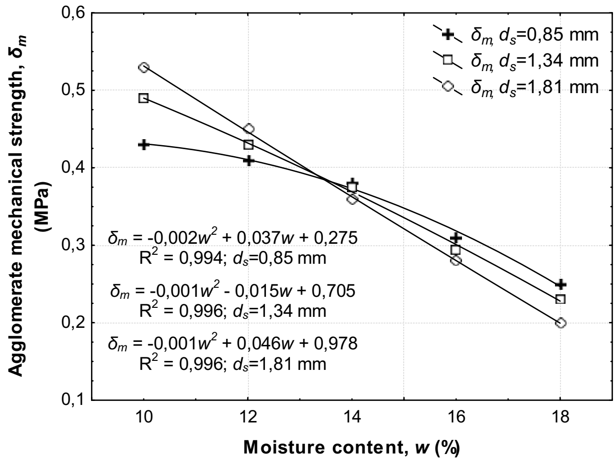

Fig. 6. Correlation between agglomerate mechanical strength δ_m and moisture content w for three average particle sizes of material d_s.

compaction of the raw material with the highest average particle size d_s = 1.81 mm.

The value of the specific compaction work $L_{c'}$ for the tested average particle size ranged from 40 J·g^{-1} (d_s = 1.81 mm, moisture content w = 10%) to 20.4 J·g^{-1} (d_s = 0.85, moisture content = 18%). Increase in moisture content (w) caused an improvement in plasticity and susceptibility of the material to compaction, which was confirmed by the decrease in the value of $L_{c'}$ work (Fig. 4) and susceptibility to compaction factor k_c (Fig. 5).

For the tested raw material, the value of coefficient of susceptibility to compaction k_c (Fig. 5) ranged from 26.8 (J·g^{-1})·[(g·cm^{-3})]$^{-1}$ (d_s = 1.81 mm, moisture content w = 10%) to 13.7 (J·g^{-1})·[(g·cm^{-3})]$^{-1}$ (d_s = 0.85 mm, moisture content w = 18%). Similar to compaction work $L_{c'}$, higher values of coefficient k_c were obtained for the raw material of d_s = 1.81 mm. Better susceptibility to compaction was found in the raw material of the lowest average particle size and of the highest moisture content. The obtained results of susceptibility to compaction k_c confirm the trend of k_c change with increasing moisture content and the change in average particle size as reported for the compaction of other raw materials [13, 21, 24].

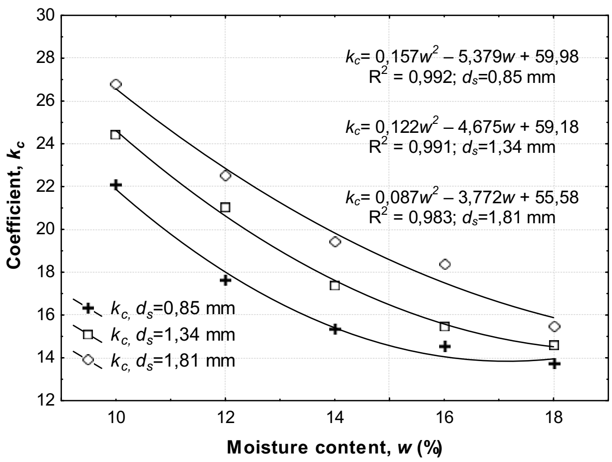

Fig. 5. Correlation between coefficient of material susceptibility to compaction k_c and moisture content w for three average particle sizes of material d_s.

Mechanical resistance δ_m for the tested material was in the range between 0.53 MPa and 0.2 MPa (Fig. 6). The results of mechanical resistance δ_m showed that strength of the agglomerates decreased with increasing moisture content of the raw material for each average particle size, which was also confirmed by the research of Missagia et al. [22]. The highest mechanical resistance was obtained for *Andropogon gerardii*, characterized by moisture content of 10% for each average particle size.

A similar variation for mechanical resistance (depending on the moisture content and the average particle size) occurred also in comparison to the agglomerate density ρ_a (Fig. 3). During compacting process of the material with the lowest moisture content, agglomerates with the highest density (Fig. 3) and mechanical resistance were produced (Fig. 6); however, because of the high compaction work (Fig. 4), the process becomes more energy intensive. In addition, an increase in the total energy consumption in the production of agglomerate, may be due to increasing the degree of grinding of the raw material. This was demonstrated in studies by Kashaninejad et al. [12]. Compression and total specific energy for making the pellets increased significantly with particle size decreasing from 3.2 to 1.6 mm.

Conclusions

The experimental results showed that the moisture content of the plant biomass (*Andropogon gerardii*) and the average particle size of the raw material significantly affect the parameters of the pressurized compaction process of the material in a closed chamber (briquetting), and have an influential effect on the mechanical strength of the resulting agglomerate.

Increasing the moisture content from 10 to 18% causes:

- Increase in the maximum density of the raw material in the chamber (ρ_c)
- Reduction in the density of the agglomerate (ρ_a) and specific compaction work ($L_{c'}$)
- Decrease of the value of k_c, coefficient, and therefore an improvement of material susceptibility to compaction
- Increase in the expansion of the agglomerate, which results in deterioration of mechanical strength of the agglomerate

However, when the average particle size was increased, agglomerates of lower density and mechanical strength are obtained. It should also be noted that higher average particle size results in higher compaction work, making the compaction process more energy-consuming.

The results obtained indicate the possibility of rational use of energy in the process of compacting the energy plants, which is favorable to economic production and environmental protection. *Andropogon gerardii* is characterized by good susceptibility to compaction and can be successfully used for the production of solid biofuels. Its use for this purpose should contribute to the further development of green, environmentally friendly energy sources. In addition, there is a need to continue research in this area in relation to other energy sources for the production of ecological solid fuels.

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