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Mechanical properties of sawdust and woodchips ☆

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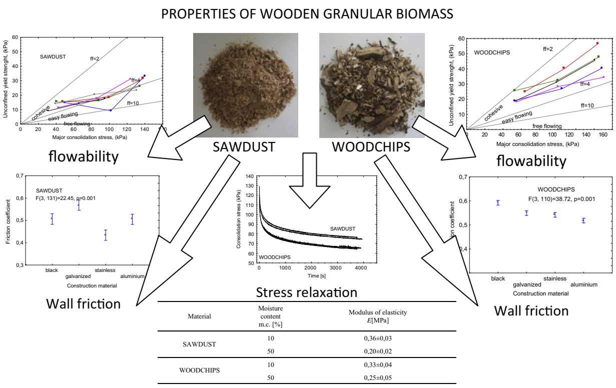
HIGHLIGHTS

- Mechanical characteristics of sawdust and woodchips useful for design and process control were determined.
- The results obtained showed distinct differences in mechanical parameters of sawdust and woodchips.
- Two kinds of commonly used materials require different adjustment and operation in technological process.

GRAPHICAL ABSTRACT



Material	Moisture content m.c. [%]	Modulus of elasticity *E*[MPa]
SAWDUST	10	0,36±0,03
	50	0,20±0,02
WOODCHIPS	10	0,33±0,04
	50	0,25±0,05

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ABSTRACT

Mechanical characteristics useful for design and process control were determined for sawdust and woodchips at five levels of moisture content. The density, the modulus of elasticity and relaxation curves were determined using uniaxial compression tester that allowed for measurement of horizontal pressure. The strength properties, the flowability and coefficient of friction against popular construction materials were determined using direct shear tester having 210 mm in diameter shear box. The modulus of elasticity was found to be under strong influence of moisture content of the material. In the case of dry woodchips modulus of elasticity of 0.33 MPa was obtained, while at 50% of moisture content it was of 0.25 MPa. Mean value of angle of internal friction for sawdust was found 27° while that for woodchips was approximately equal to 33°. Effective angle of internal friction ranged from 34° for sawdust to 42° for woodchips. Flow index of sawdust was characteristic for cohesive/easy flowing materials while it was characteristic for cohesive materials in the case of woodchips. Strong negative correlation was observed in relationship between angle of internal friction and moisture content of sawdust. Weak or no correlation of cohesion versus moisture content relationships was observed for both tested materials, while cohesion was found under strong influence by consolidation stress.

Friction against construction materials was found higher in the case of woodchips. No influence of consolidation stress on coefficient of friction was noted. With an increase of moisture content above 30% for sawdust and 20% for woodchips decrease in friction coefficient took place.

1. Introduction

Knowledge of mechanical properties of granular biomass and its blends with coal is necessary for design and efficient operation of

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equipment for handling, storage and processing [26,7,9,8,10,6,25]. Biomass is widely used as energy source directly or in the form of briquettes or pellets that is a granular material. The most important technologies of process engineering involving granular biomass are pneumatic conveying, transport, size reduction, densification, mixing (blending), segregation, weighing, metering, packaging and bagging or storage. To assure reliable processing and efficiency of equipment exact values of material parameters are necessary [8,9,1]. Of particular interest in bioenergy practice are such characteristics of granular biomass such as density, strength parameters, elasticity and flowability. Density, that is mass divided by volume, is one of the fundamental parameters of granular materials and also granular biomass [15,7]. Knowledge on the exact value of the density of granular material is very important for numerous practical applications.

The density of a material has a significant effect on its mechanical characteristics. It is the parameter that is used for the estimation of pressure exerted by granular material against the structure of the bin or silo. It is also necessary for accurate estimation of container capacity.

Strength properties the angle of internal friction φ, the effective angle of internal friction δ and the cohesion C and methods of their determination are standardized in design codes (e.g. Eurocode 1 [5]). These parameters are crucial for estimation of pressures of granular materials exerted on storage structures, as well as for design of installations to assure reliable flow. These parameters are also used in numerical modeling of processing of such materials. The angle of internal friction φ measures the ability of a sample of granular material to withstand a shear stress. It is the angle of inclination of shear stress versus normal stress characteristic, that is assumed linear in very popular Mohr–Coulomb yield condition: $\tau = \sigma \cdot tg\varphi + C$. The cohesion C represents the shear strength under zero normal stress. The value of cohesion C strongly depends on the consolidation stress so cannot be regarded as a fixed property of the granular material. The effective angle of internal friction δ is used for estimation of conditions for the mass flow or funnel flow in the hopper. With this parameter the maximum slope angle of the hopper wall against the vertical which ensures mass flow can be determined. The modulus of elasticity E characterizes elastic deformation of granular bedding under mechanical load. Design of equipment for handling and processing of granular material requires experimental value of this parameter that depends on normal pressure. These parameters are in particular interest of professionals using computer aided design that recently has become very common tool [3]. Flowability, for some materials is used as a measure of the quality of granular product that influences its end-use value. Variation in flowability of ingredients may be a significant source of errors during the weighing and mixing that result in non-uniformity of the end product (such as pellets or briquettes). The flow function *FF* represents the strength of the consolidated material that must be surpassed to initiate flow. Regarding values of flow function granular materials may be characterized as free flowing, easy flowing, cohesive and strong cohesive.

Another aspect of mechanical properties of granular materials stored in bulk in silos and handled in technological processes is frictional interaction with construction materials. This behavior is described by friction coefficient μ which is the tangent of inclination of linearized relationship between shear stress and normal stress during sliding of a sample of granular material against plane surface of construction material. The interaction between granular biomass and machinery during operation for example pelleting or transport is crucial factor to attain stability in technological process. Moisture content is the main factor which determines interaction between surface and granular material. There are some papers that consist of data about friction against construction materials. Kinematic wall friction coefficient of reed canary grass powder was determined by Larsson [14] at low – from 0.5 to 7.5 kPa and at high – from 23 to 275 MPa normal stresses. At low normal stress 0.5–7.5 kPa the kinematic wall friction was positively correlated to moisture content and negatively correlated to normal stress. Friction coefficient was obtained in a range from 0.15 to 0.25. In the case of high normal stress kinematic wall friction also decreased with increase in normal stress but no correlation with moisture content was observed. In this case maximal value of coefficient of 0.6 was found for 11.1% and 15.8% of m.c., while minimum, about 0.1 for m.c. 27% and 8.9% at normal stress 250 MPa was found.

Mechanical properties of granular biomass are strongly influenced by particle size distribution and moisture content [6]. The handling behavior of two kinds of granular biomass was analyzed by Gil et al. [7]. The authors analyzed influence of moisture content in a range from 7% to 27%, particle size distribution and shape of milled poplar and corn stover. The authors found that smaller particle size improved the relative displacement between particles and concluded that hooked and long shape of bigger particles resulted in higher cohesive force and interlocking particles each other. Increase in moisture content resulted in higher angle of internal friction and effective angle of internal friction, as well as in a decrease in flowability. Mattsson and Kofman [16] observed the bridging effect occurring in chopped biomass of elongated shape produced from willow. Littlefield et al. [15] examined an influence of granular biomass particle size and moisture content of pecan shells. Authors determined density, compressibility, angle of internal friction parameters and flowability. The authors found that poured bulk density and tapped bulk density decreased, and compressibility increased with increase in particle size and moisture content. Flowability decreased with increase in moisture content, while values of cohesion increased. Average angle of internal friction was not significantly affected by moisture content in these examinations. Ileleji and Zhou [11] measured the angle of repose of corn stover of various particle sizes and moisture contents. Both parameters were found dependent on considered factors. Guo et al. [8,9] examined changes of discharge from hopper and flowability of mixtures of coal and granular biomass i.e. rice straw and sawdust. The authors found that biomass particles could improve flowability of pulverized coal. Similar results were reported by Przywara et al. [23]. Zulfigar et al. [26] observed that addition of sawdust to coal leads to reduction of the strength of the bulk. Addition of woodchips to coal had no effect on strength of the material. Moreover, these authors observed that mixing coal with sawdust may produce flow stops, while addition of woodchips may facilitate discharge. Physical form of biomass has strong influence on strength characteristics of granular biomass and its blends with coal. The physical properties of three types of biomass: wood pellets, woodchips and torrefied pellets were determined by Wu et al. [25]. The authors showed that wood pellets as a material standardized in dimension and shape had the best flowability, followed by torrefied pellets and woodchips.

Only a few papers addressed flowability and friction properties of granular biomass, and we did not find data regarding moduli of elasticity of woodchips and sawdust, which is the main factor characterizing compaction. Still attempts are undertaken to elaborate new methods for determination of the flowability of such materials. Miccio et al. [18] estimated solid biofuel flowability with Schulze Ring Shear Tester and arching phenomena in silo discharge. The authors proposed the original apparatus where the sample of granular biomass was loaded and consolidated. Moreover, new procedure was proposed, based on the Jenike's arch stability analysis to evaluate the flow function of the material from the critical orifice diameter for arching.

Granular biomass materials distinctly differ from conventional granular solids used in the process industry, but there is a scarce knowledge of their flow properties of [17,26]. Also insufficient is information in the literature regarding strength and frictional properties of woodchips which pose serious problems in handling [24].

The objective of reported project was to determine mechanical properties of two kinds of granular biomass: sawdust and woodchips at five levels of moisture content and under three levels of normal pressure. Moisture contents and pressures of testing were adopted to reflect conditions of operation of handling equipment in practice. The density, the modulus of elasticity and relaxation curves were determined in uniaxial compression test. To determine the strength properties, the flowability and coefficients of friction against popular construction materials direct shear test was used.

2. Materials

Two types of granular biomass, widely used in generation of green energy, sawdust and woodchips were chosen as experimental materials. Sawdust, by-product of production of furniture was obtained from local factory, while woodchips were donated by local horticultural operation. After delivery materials were dried in thin layer in laboratory conditions. Then, to obtain desired levels of moisture contents of 10%, 20%, 30%, 40% and 50%, distilled water was added and the materials were mixed for 15 min of each hour through 24 h in laboratory mixer. The levels of moisture content corresponded to those existing in technological practice where biomass of various conditions is delivered depending on place of origin, season and weather. Miccio et al. [17] examined wood biomass in alike range of moisture content, from 10% to 55%. Nyström and Dahlquist [21] reported that changes in granular biomass of moisture content from 10% to 64% resulted in serious transport and storage problems. Moisture content was measured by weighing 200–300 g samples before and after 24 h drying in 105 °C in laboratory oven. Particle size distribution of sawdust and woodchips is presented in Table 1. In the case of sawdust sieve analysis was performed during for woodchips the length of particles was measured with digital caliper gauge. In both cases 0.5 kg of material was taken into account.

3. Methods

Requirements for equipment, procedures and analysis techniques for the determination of above enlisted properties of granular materials are described in Eurocode 1 [5]. The diameter D of direct shear apparatus should be at last 20 times the maximum particle size and not less than 40 times the mean particle size. The height H should be between 0.3 and 0.4D. The maximum particle size is limited to ensure that any interaction of the material with the wall of the shear cell will not influence the measured property. Modulus of elasticity E and density ρ of materials were determined in uniaxial compression tester with possibility of measurement of horizontal stress. The apparatus and method of determination modulus of elasticity were as earlier described in Molenda and Stasiak [19] and Molenda et al. [20]. Poured density ρ_0 was determined as the ratio of mass and volume of material filling the apparatus chamber 210 mm in diameter and 80 mm high. Then the sample was vertically compressed to the reference stress σ_r of 120 kPa using a universal testing machine at a constant loading rate of 0.35 mm min^{-1}. Then unloading took place with the same speed. Based on unloading part of the experimental curve the modulus of elasticity was determined. Tests were performed in three replications. In the second phase of uniaxial compression testing, characteristics of relaxation of compression stress were determined. When compaction vertical stress attained 120 kPa the beam of universal testing machine was stopped and vertical stress was recorded during one hour.

Table 1
Particle size distributions of sawdust and woodchips.

Material	Particle size (mm)	Fraction (%)	Material	Particle size (mm)	Fraction (%)
SAWDUST Birch-tree	<0.2	9.3	WOODCHIPS Poplar	<3	14.3
	0.2–0.3	5.9		3.0–8.0	33.8
	0.3–0.4	0.4		8.0–16.0	23.3
	0.4–0.5	4.0		16.0–30.0	18.3
	0.5–0.6	4.1		30.0–70.0	8.4
	0.6–0.8	5.1		70>	1.9
	0.8–0.9	1.8			
	0.9–1.6	25.9			
	1.6–2.0	7.8			
	2.0–3.2	18.6			
	3.2–7.0	14.9			

Determination of strength, flowability and friction against construction materials was conducted in direct shear tester which is 210 mm in diameter. The tests followed Eurocode 1 [5] procedure for consolidation reference stresses σ_r of 20, 40 and 60 kPa and speed of shearing V of 0.17 mm s^{-1}. The seemingly high range of consolidation stresses used in our testing corresponds to loads in storage silos approximately 20 m that are used in energy plant where continuity of energy production must be maintained in co-firing with standard coal fuel.

Based on the experimental curves, the angle of internal friction φ, the effective angle of internal friction δ, flow function FF, cohesion C, and coefficient of wall friction μ (on black, galvanized, stainless steel and aluminum samples) were determined. The range of consolidation stresses occurs in storage systems of granular biomass in energy plant where battery of silos of 20 m high is necessary to ensure the continuity of energy production in the process of firing and co-firing with standard coal fuel. Determination of yield locus was performed for two values of consolidation stress σ_r and for ½σ_r during shearing. In both cases consolidation of material was done with σ_r. From two values of shear stress obtained under two values of consolidation stress yield loci were obtained. The procedure was performed following Eurocode 1 [5]. Next, Mohr's circles were drawn, which enabled calculation of the values of unconfined yield strength σ_c and major consolidating stress σ_1. The flow function FF was calculated as the $\sigma_c(\sigma_1)$ relationship (e.g. [20]). All experiments were performed in three replications. The ANOVA simple main effect test was performed with STATISTICA 10, StatSoft Inc. 2011.

4. Results and discussion

4.1. Density

The results of determinations of densities are presented in Table 2. The poured density ρ_0 of sawdust 10% in moisture content was equal to 312 kg m^{-3}, while ρ_0 of 50% in moisture content

Table 2
Parameters obtained in uniaxial compression tester.

Material	Moisture content m.c. (%)	Poured density ρ_0 (kg/m^3)	Consolidated density ρ_1 (kg/m^3)	Modulus of elasticity E (MPa)
SAWDUST	10	312 ± 5	708 ± 5	0.36 ± 0.03
	50	320 ± 6	750 ± 4	0.20 ± 0.02
WOODCHIPS	10	282 ± 12	500 ± 10	0.33 ± 0.04
	50	320 ± 11	660 ± 11	0.25 ± 0.05

sawdust was found slightly higher of 320 kg m^{-3}. Similar tendency was observed in the case of woodchips where poured density of dry material was of 282 kg m^{-3} while ρ_0 of wet material was of 320 kg m^{-3}, thus equal to that of wet sawdust. About 10% higher value of poured density in the case of sawdust is the result of dimension of particles, their shape and homogeneity. Particles of woodchips which are large and heterogeneous in shape formed a deposit with lot of free space. In the case of woodchips there is problem of autosegregation that results in uneven density in various areas of volume of the sample. In the case of wet materials equal values of density were obtained for woodchips and sawdust. Probable reason of such behavior is the lubricating action of water with the increase of moisture content that allowed for denser packing of wet woodchips. Similar result was obtained by Littlefield et al. [15] for pecan shells. Higher value of density of sawdust with higher moisture content was noted by Miccio et al. [17]. The differences could be attributed to different particle size distributions of experimental materials. Values of poured density obtained for woodchips are comparable with the results of Wu et al. [25] where the authors determined bulk density of woodchips of different length of particles. Density of particles length in a range 0–20 mm was of 228 kg m^{-3} while for particles length in range 0–100 density of 256 kg m^{-3} was obtained.

In the case of consolidated density ρ_1 of dry and wet sawdust over 100% increase was observed. Lower increase of density, below 100% was obtained for woodchips. Lower relative increase in density of woodchips after consolidation is probably a result of stiffer construction of the bulk composed of large particles. The highest value of ρ_1 of 750 kg m^{-3} was obtained in the case of wet sawdust. Wet particles of sawdust easily undergo deformation than dry particles. In the case of woodchips consolidated densities of 500 kg m^{-3} and 660 kg m^{-3} were found for 10% and 50% of moisture content, respectively. Opposite behavior of density with moisture content increase was observed by Littlefield et al. [15] for pecan shells. Bulk and tap density of pecan shells significantly increased with decrease in particle size. Densities of pecan shells were higher than those obtained for sawdust and woodchips in reported investigations. Bulk density in a range from 417 to 470 kg m^{-3} was found, while tap density ranged from 486 to 601 kg m^{-3} dependent on the particle sizes of pecan shells.

4.2. Elasticity

Modulus of elasticity *E* was found to be under strong influence of moisture content and was higher in the case of dry materials. Higher water content resulted in easier deformation of individual particles. Additional factor facilitating deformation might be lubricating action of free water present in particles contacts. Higher decrease of modulus of elasticity with an increase in moisture content was observed in the case of sawdust. The *E* of dry sawdust was equal to 0.36 MPa, while it was of 0.20 MPa for dry material. In the case of woodchips values of *E* of 0.33 MPa and 0.25 MPa were found for dry and 50% in moisture content samples (see Table 2). These results corroborated our earlier findings concerning granular materials produced of cereal grains [20]. In the case of cereals the values of moduli *E* were even 100 times higher in tests performed in comparable conditions. Values for wheat decreased from 22 to 11 MPa with an increase in moisture content from 10% to 20%.

4.3. Relaxation

Consolidation stress σ versus time *t* relationships for relaxation test are presented in Fig. 1 in two replications. Distinct differences in behavior of the two materials were observed. In the case of woodchips decrease of consolidation stress was faster than in the case of sawdust. After 1 h of relaxation stress decreased from 120 kPa to 75 kPa and to 65 kPa in sawdust and woodchips, respectively. After freezing of the cover of the uniaxial compression tester woodchips as nonhomogeneous material starts reorganization of internal structure caused faster decrease in stress.

4.4. Direct shear test

From direct shear tests relationships between shear stress and relative displacement were obtained. No oscillations were observed on tests curves that sometimes occur for materials of irregularly shaped and deformable particles. Similarly, smooth experimental curves were obtained by Miccio et al. [17] for sawdust in Schulze Ring Shear Tester. In Fig. 2 relationships between τ and $\Delta L/D$ are shown obtained for materials of different moisture content at maximum consolidation stress of 60 kPa. Differences in shear stress value for sawdust and woodchips were observed in the whole range of consolidation stress. In the case of 10% m.c. no distinct difference in values of shear stress for both the materials and three values of consolidation stress were found (see Fig. 3).

Weak repeatability of results was obtained in the case of woodchips. In the case of sawdust shear stress plots for three replications were very close. In the case of sawdust 50% in m.c. repeatability of curves sawdust was not as good. For each value of consolidation stress values of shear stress were 50% lower than those obtained in the case of 10% m.c. Different tendency was observed in woodchips, where shear stress in the whole range of consolidation stress did not change and was not influenced by moisture content. In the case of sawdust shear stress reached asymptotic value while the curve for woodchips did not stabilize. Decrease of shear stress with an increase of moisture content of sawdust observed in our testing was opposite to results reported by Przywara et al. [22] for forest biomass. Our results for woodchips are in agreement with those of these authors probably due to physical similarity of woodchips and forest biomass.

4.5. Internal friction and flowability

Based on shear stress values linear yield loci were drawn and parameters of Mohr–Coulomb yield condition were determined following Eurocode 1. Fig. 4 shows mean values of angle of internal friction φ, effective angle of internal friction δ and flow index *i* with 95% confidence intervals calculated for all tested levels of moisture content and consolidation stress.

The angle of internal friction, effective angle of internal friction and flow index were found significantly higher for woodchips than for sawdust. Mean value of angle of internal friction for sawdust

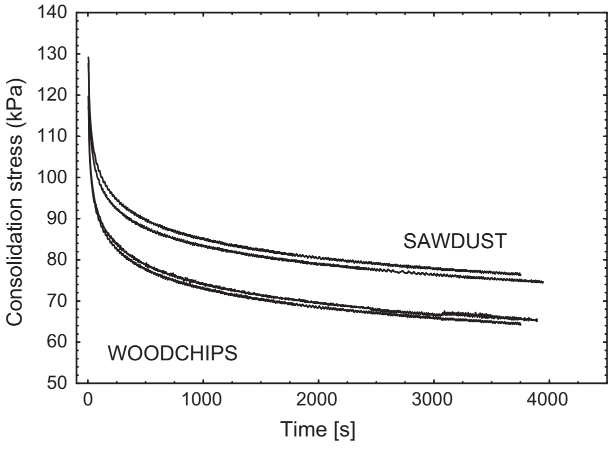

Fig. 1. Relaxation of normal stress in uniaxial compression.

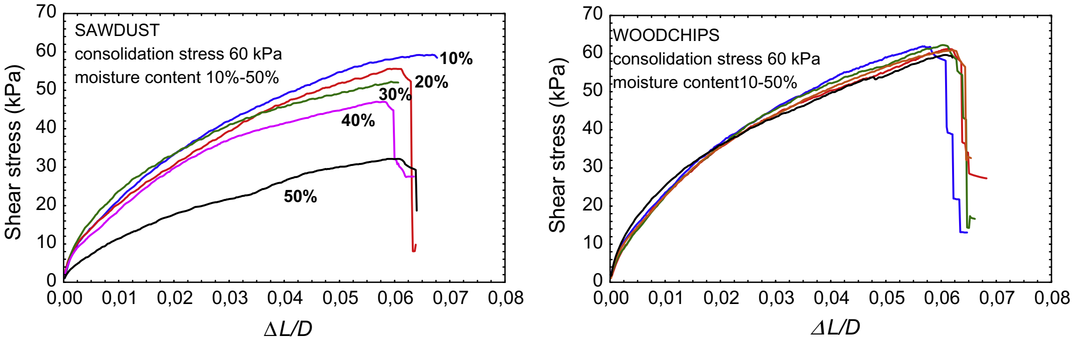

Fig. 2. Experimental curves obtained in direct shear test for sawdust and woodchips at 60 kPa consolidation stress.

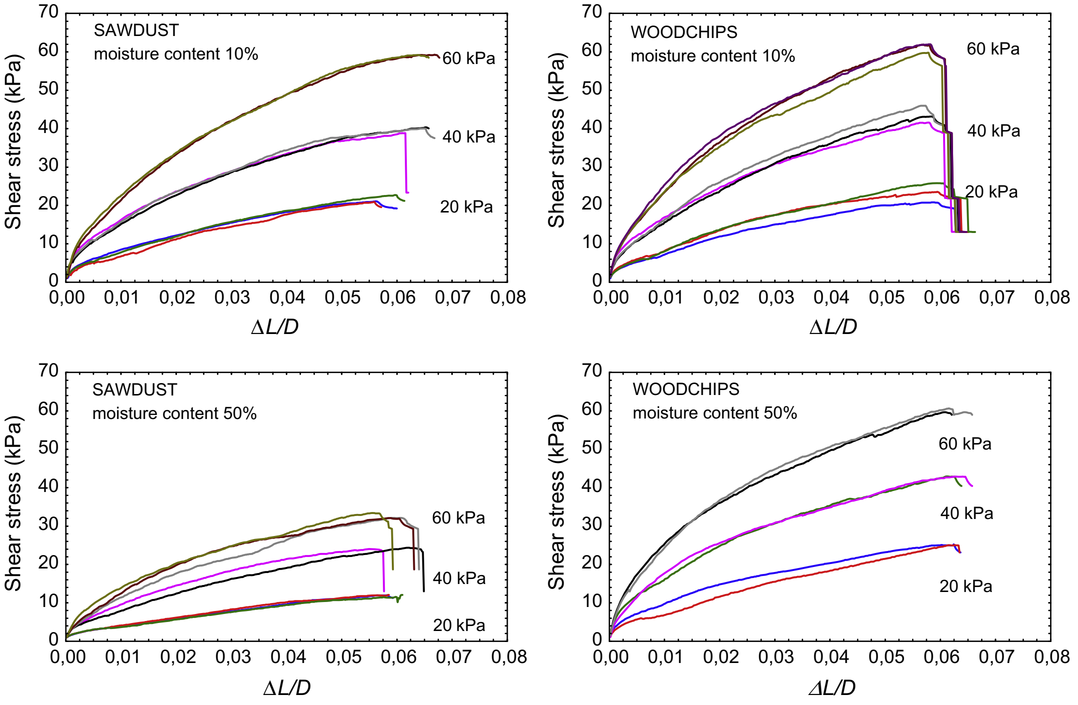

Fig. 3. Experimental curves obtained in direct shear test for sawdust and woodchips at 10% and 50% of moisture content in a range of consolidation stress.

was 27°, while that for woodchips was of approximately 33°. Effective angle of internal friction of 34° was found for sawdust and 42° for woodchips. Flow index for sawdust was characteristic for cohesive/easy flowing materials, while in the case of woodchips mean value of this parameter was characteristic for cohesive materials. No effect of moisture content on flow index was noted. Higher strength parameters and weak flowability of woodchips are the result of more nonhomogeneous and hook in shape granules. Effective angle of internal friction for woodchips was lower than this obtained for woodchips by Wu et al. [25].

Fig. 5 shows angle of internal φ as influenced by m.c. and consolidation stress σ_r. Mean value of φ for sawdust was found under significant influence on m.c. (level of significance $p < 10^{-3}$) and decreasing from 33° to approximately 16° with an increase in m.c. from 10% to 50%. Values of φ with 95% confidence intervals and φ(m.c.) regression line with a pair of dotted lines representing the prediction limits are presented in Fig. 5. In the case of sawdust increase in moisture content from 10% to 50% resulted in decrease of angle of internal friction. Coefficient of linear correlation r of φ(m.c.) relationship found equal to 0.783 was significant at p of 0.001. No correlation with consolidation stress was observed. Calculated mean values of φ varied from approximately 25° for minimum σ_r to approximately 27° for 40 kPa of consolidation stress.

No significant differences between mean values of φ for woodchips were noted. The angle of internal friction was approximately equal to 33° for all levels of m.c. and consolidation stress. Results of angle of internal friction in general agree with results reported in Miccio et al. [17] and Barletta and Poletto [4] at low consolidation stresses for experiments performed in Schulze ring shear tester. These authors also did not observe correlation between angle of internal friction and consolidation stress. The values of angle of internal friction from their experiments varied from 40.7° to 54.7°. Values of angle internal friction obtained in reported project are comparable with those obtained for chopped poplar by Gil et al. [7] where angle of internal friction in the range from 30° to 32° was obtained. Values of the effective angle of internal friction in the range from 33° to 36° were lower than those estimated for woodchips and comparable to those of sawdust. Our values of angle of internal friction were lower also from 46° reported by Wu et al. [25] for woodchips. The difference in value of internal friction is probably a result of different particle size distributions. Milled

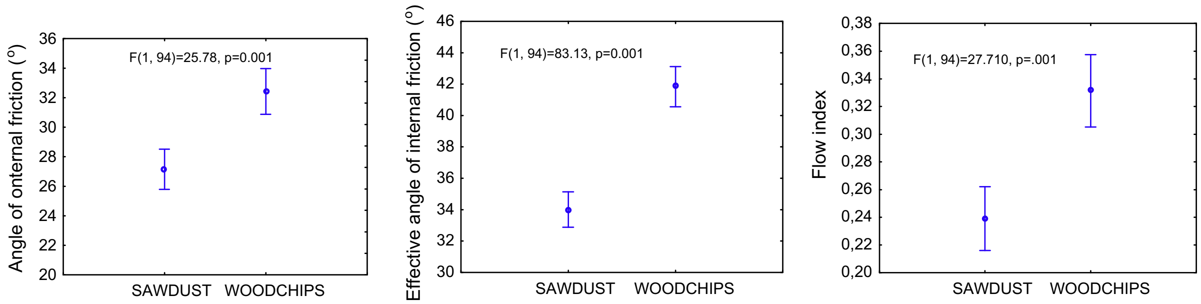

Fig. 4. Mean values and 95% confidence intervals of determined parameters for all tested levels of moisture content and consolidation pressure for sawdust and woodchips.

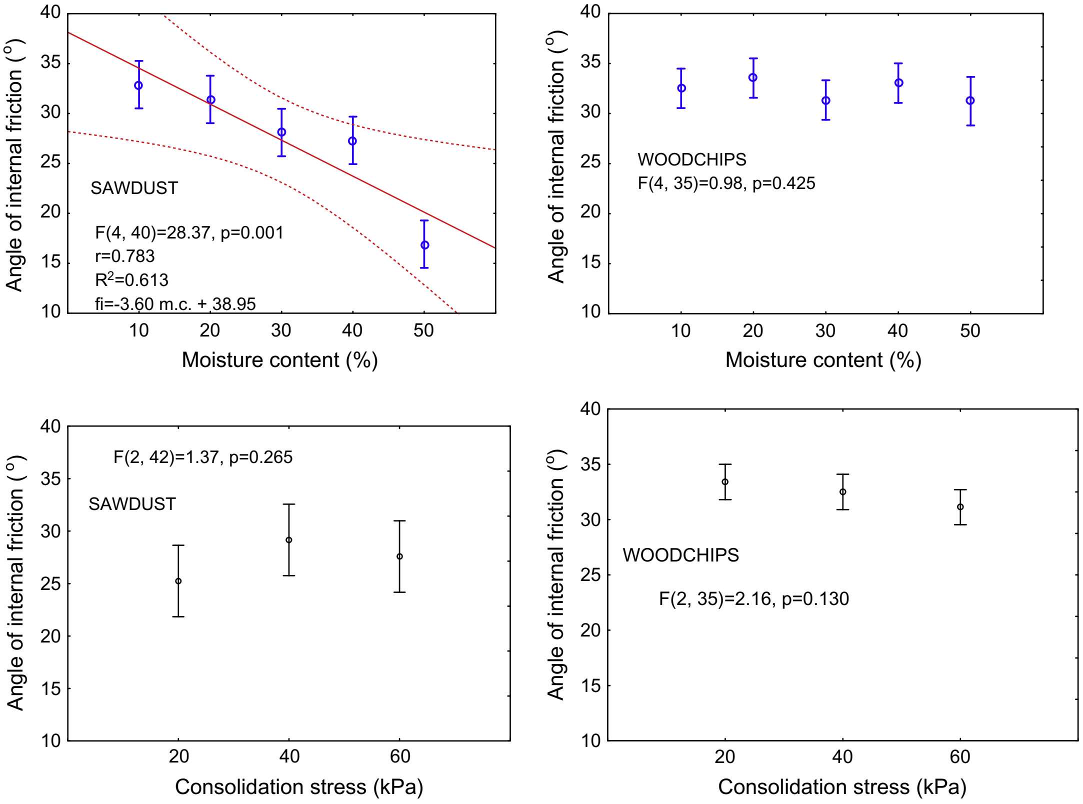

Fig. 5. Mean values and 95% confidence intervals of angle of internal friction for sawdust and woodchips for five levels of moisture content and three levels of consolidation stress.

wood biomass usually flows easier than the chopped one and such result of Gil et al. [7] agrees with our results for sawdust and woodchips. Values of angle of internal friction obtained within this project are smaller than those given by Littlefield et al. [15] for pecan shells of various fractions where mean value of this parameter equal to 41.3° was obtained.

Calculated mean values of C were almost two times higher for woodchips than for sawdust. In the case of woodchips mean value of cohesion calculated for all consolidation stresses and in a whole range of m.c. was about 9.5 kPa while for sawdust it was about 5.5 kPa. In Fig. 6 mean values of cohesion of sawdust and woodchips are presented. In the case of sawdust weak ($r = 0.232$), but significant at $p = 0.001$ negative linear correlation with moisture was observed. The highest value at minimum moisture content 10% was of approximately 7 kPa and decreased to approximately 5 kPa at 50% m.c. Strong positive correlation was found in the case of $C(\sigma_r)$ relationship with coefficient of linear correlation $r = 0.862$. Mean values of cohesion increased from about 4 kPa at 20 kPa of consolidation stress to about 8 kPa at 60 kPa consolidation stress.

In the case of woodchips no correlation between C versus m.c. was observed. Maximum mean value of cohesion of 11 kPa was obtained for 20% of m.c. Strong positive linear correlation in cohesion versus consolidation stress relationship was found with $r = 0.857$. In this case cohesion varied from about 5 to about 13 kPa. Fig. 6 presents $C(\sigma)$ regression lines with two pairs of dotted lines representing the 95% confidence intervals and prediction limits. Values of cohesion obtained in our experiments are distinctly higher than those reported by Miccio et al. [17] or Barletta and Poletto [4] for experiments performed in Schulze ring shear tester. Authors obtained maximal value of cohesion for sawdust equal to 0.15 kPa at 0.7 kPa of consolidation stress and it was about 2.5% the value obtained in our tests. Most probably difference is a result of difference in applied consolidation stresses. Cohesion values obtained in this project are higher than those

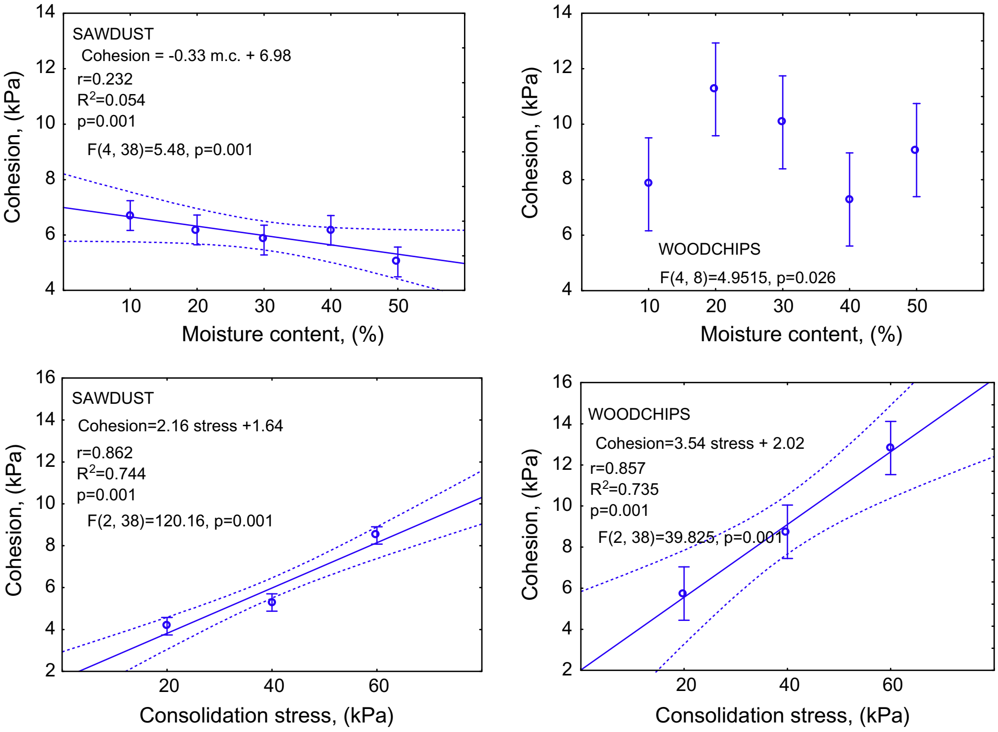

Fig. 6. Mean values of cohesion with 95% confidence intervals determined in direct shear tester for tested materials.

obtained by Gil et al. [7] for poplar and corn stover where *C* did not exceed 1 kPa, probably due to differences in apparatuses and consolidation stresses used. Values of cohesion for nontreated barley, canola, oat and wheat straws obtained by Adapa et al. [1] in a range of consolidation stress from 10 to 40 kPa are comparable with our results.

The different behavior of sawdust and woodchips during shear test and decrease in cohesion and friction with increasing moisture content in the case of sawdust could be the reason of different characteristic of wet granular material state as were discussed widely for powders by [2]. Wet granular materials can be classified into three characteristic physical states: pendular, in which discrete liquid bridges bind the particles together; the funicular state, in which larger amount of liquid is present and the capillary state in which particles are enclosed in saturated clusters. In the case of woodchips there is not enough liquid to lubricate the particles and this is in opposite to sawdust. In the case of sawdust the interparticle friction forces and particle interlocking for higher moisture content are lower.

In Fig. 7 flow functions *FF* of experimental materials for all moisture content tested are presented. No clear tendency of variation of *FF* with moisture content was observed. In the case of sawdust flow functions were characteristic for cohesive materials and were close to $i = 0.25$ line which divided easy flowing and cohesive materials.

The highest values of *FF* were obtained in the case of woodchips, probably due to higher nonhomogeneity of this material. The results obtained for woodchips and sawdust are in good agreement with results obtained by Barletta and Poletto [4]. The authors determined flow characteristics for sawdust of two dimension of particles, dry sawdust with particles that passed through 4 mm sieve and moist sawdust sieved through 2 mm sieve. Dry material was in the limit between cohesive and easy flowing, while wet sawdust was characterized as very cohesive and cohesive. Our results agree with Gil et al. [7] investigations where the authors concluded that biomass of particles which are bigger, more complex in shape flowed worse. Our results are also comparable with results of Mattsson and Kofman [16] where a tendency was noticed that granular biofuels with higher nominal particles length showed a higher bridging tendency. The tendency to bridge depended on proportion of long and hook shaped particles. The long and hook shaped particle are woodchips in our experiments. Worse flowability of coal blended with woodchips in comparison with coal blended with sawdust was observed by Zulfigar et al. [26]. Their results are alike obtained in our testing. Also results of Littlefield et al. [15] on pecan shells of different particle sizes showed that fine particles flowed easier. The authors concluded that increase in moisture content resulted in a reduction in flowability of pecan shells.

4.6. Wall friction

From wall friction shear tests the values of friction coefficient μ were determined (see Fig. 8). The friction against construction materials is one of the important physical properties because it influences flow pattern and pressure distribution in granular deposit. Mean values of this parameter calculated for all consolidation stresses and moisture contents were significantly higher for woodchips. The coefficient of friction of woodchips was of 0.55 and for sawdust 0.50 (see Fig. 8a). Coefficients of friction measured on black steel were: 0.5 for sawdust and significantly higher, and 0.6 for woodchips. For galvanized steel friction coefficients were about 0.55 for both materials.

Friction coefficient against stainless steel for woodchips was equal to 0.55 and higher than this for sawdust approximately equal 0.45. In the case of aluminum the coefficients were both found of about 0.5. Moisture content strongly affected friction coefficients of sawdust and woodchips (see Fig. 8b). The mean values increased with an increase in moisture content to 30% in the case of sawdust and to 20% for woodchips. Following increase in moisture content resulted in distinct decrease in friction coefficient in the case of sawdust and slight decrease in the case of woodchips. This effect

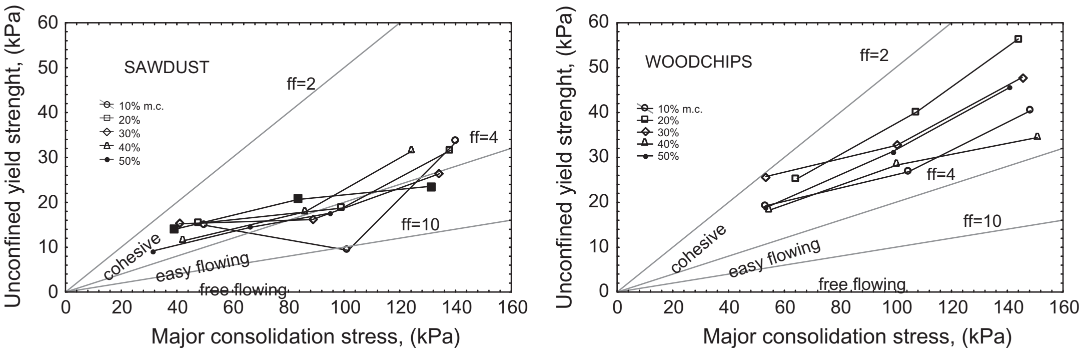

Fig. 7. Flow functions of experimental materials.

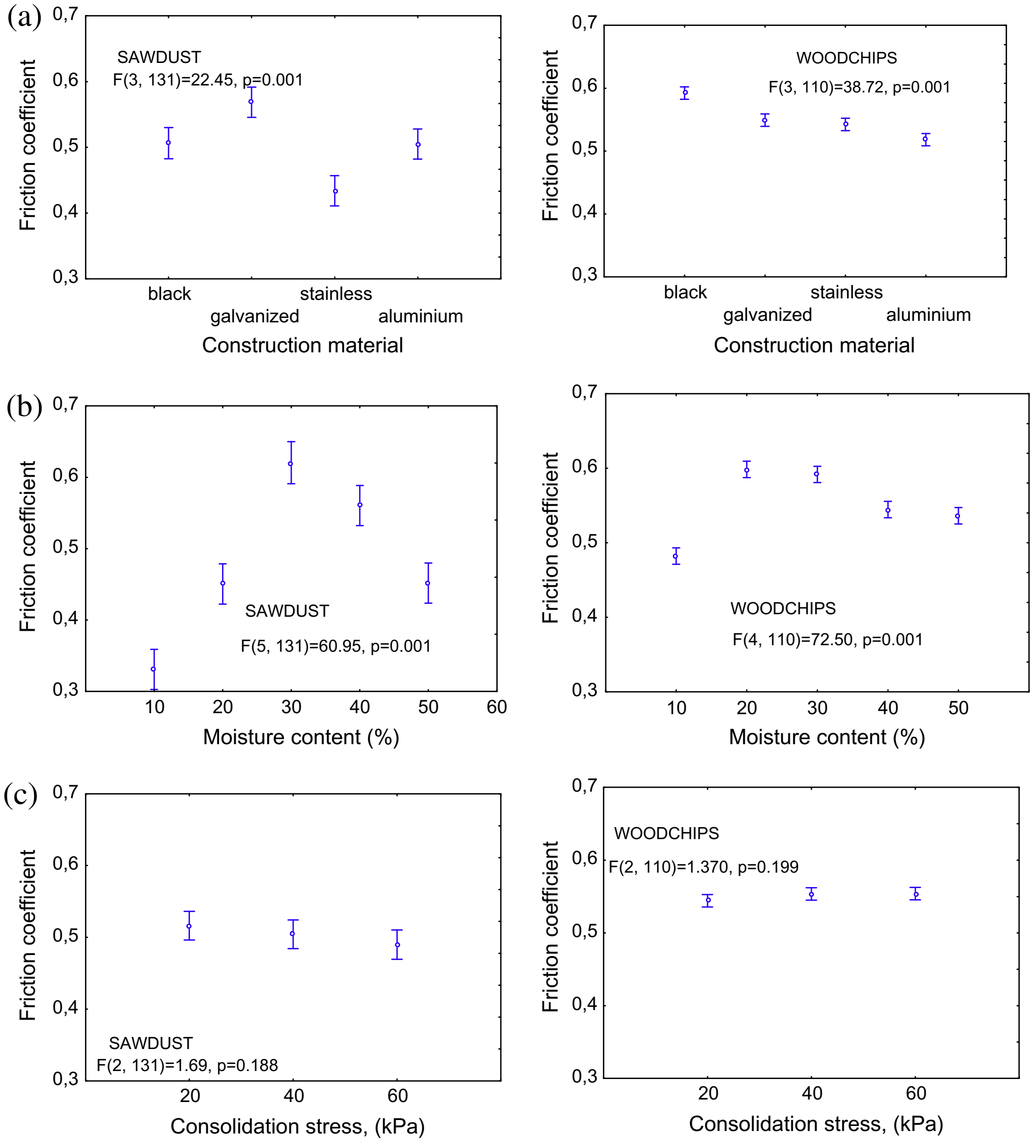

Fig. 8. Mean values of friction coefficient against construction materials at 5 levels of m.c. and three levels of consolidation stress. Mean value in dependence of (a) material, (b) moisture content and (c) consolidation stress.

is probably a result of lubricating action of free water between particles and flat surface. No influence of consolidation stress on coefficient of friction was observed (see Fig. 8c). Mean values were about 0.5 for sawdust and about 0.55 for woodchips. Similar results were obtained for woodchips of different m.c. by Ima and Mann [12]. These authors determined friction coefficient at m.c. from 37% to 60% and obtained stable value of approximately 0.52. Results of friction against construction materials are in good agreement with those given by Gil et al. [7] and Zulfigar et al. [26] where angles of wall friction were found in a range from 22° to 27° that corresponds to μ from 0.4 to 0.5. Values obtained in presented project are also in good agreement with results obtained by Wu et al. [25] where coefficients of friction of woodchips were obtained 0.50 on mild steel and 0.60 on stainless steel. Adapa et al. [1] measured coefficients of friction for untreated barley, canola, oat and wheat straws under normal load from 10 to 40 kPa and obtained results comparable with ours. Using values of effective angle of internal friction and angle of wall friction, the minimum hopper outlets diameter was calculated. Jenike's design procedure for flow [13] provided even up to 1.5 m diameter for woodchips and about 1 m diameter for sawdust for the black steel. The diameters were much higher than those obtained by [4] for biomass which did not exceed 0.5 m. The differences between data presented by Barletta and Poletto and the ones presented in this paper result from smaller consolidation stress applied in described experiments. Our results appertain rather large storage structures such as silos 15 m in diameter used in power plants. In such silos discharge systems with screw conveyors inside the silo are often used.

5. Conclusions

Mechanical parameters of two kinds of granular biomass, sawdust and woodchips at different moisture contents were determined. Estimated parameters are necessary for design and operation of process equipment involving high column of material. The results obtained showed distinct differences in mechanical parameters of sawdust and woodchips, which suggested that these two kinds of commonly used materials require different adjustment and operation in technological process.

Increase in moisture content of both materials resulted in an increase of poured and consolidated density. Values of modulus of elasticity of sawdust and woodchips are comparable and decrease with an increase in moisture content. Relaxation of stress after consolidation is faster in the case of woodchips.

Strong influence of moisture content on maximum shear stress was observed in the case of sawdust while no influence of moisture content was noted in the case of woodchips.

Woodchips were found stronger material of worse flowability. Angle of internal friction for sawdust was found in strong negative correlation with moisture content. Both materials have shown weak or no correlation of cohesion versus moisture content, while strong correlation between cohesion and consolidation stress for both materials was found.

Coefficients of friction steel and aluminum sheets were higher in the case of woodchips. No effect of consolidation stress on friction coefficients was noted. For both, sawdust and woodchips the effect of free water lubrication was observed. After reaching 30% of m.c. for sawdust and 20% of m.c. for woodchips friction coefficient decreased.

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